SOME ISSUES IN DESIGN AND OPERATIONAL CHARACTERIZATION OF AGV BASED MATERIAL HANDLING SYSTEMS IN FMS ENVIRONMENT

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CERTIFICATE

Certified that the work contained in the thesis entitled "*Some Issues in Design and Operational Characterization of AGV Based Material Handling Systems in FMS Environment*", by "*Sunil Rajotia*", has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

An Automated Guided Vehicle System (AGVS) is a system featuring battery powered, driverless vehicles with programming capabilities for path selection and positioning. AGVs are seen as ideal material handling device for integrating process automation. They are gaining wider acceptance as primary material handling equipment in an FMS. Potential benefits of an AGVS include low labour costs, tighter control over materials and productivity monitoring, flexibility in routeing, adaptability to a variety of facility layouts, etc. An AGVS can be reconfigured more easily to accommodate changes in production volume, product mix, product routeing, or equipment interfacing requirements than is possible with most other material handling systems.

Achievement of high performance for an AGVS is influenced by several design variables, which include specifying the type and the size of required vehicle fleet necessary to adequately perform a given level of handling task, specifying appropriate guide path configuration, locating load transfer stations, designing vehicle buffering areas, specifying vehicle dispatching and routeing strategies, managing traffic, specifying unit load sizes, specifying central or local W-I-P storage capacity, etc. Operating dynamics of an AGVS characterize the relationship between the AGVS design parameters and AGVS operating behaviour which includes empty vehicle travel, variation in W-I-P storage queues, vehicle blocking as a result of path contention, and shop locking phenomenon. The design and operational characterization of an AGVS presents difficulties common to many design problems. These include the presence of multiple decision variables whose interaction and performance impacts may be difficult to predict without detailed computational analysis. Usually this analysis involves computer simulation.

The present work has been carried out with an objective of studying the interactions among some of the important decision variables of AGVS and evaluating their effect on system operating behaviour. The aim is to specify appropriate levels of design parameters and control strategies within the manufacturing scenario that will achieve an acceptable level of performance based on shop throughput performance measure. For this purpose, two design parameters — AGV fleet size and flow path configuration, and two operational control measures — vehicle dispatching strategies and vehicle route planning have been addressed. Analytical modelling techniques that have been used in the present work include mixed integer linear programming for estimation of empty vehicle travel, heuristic rules for configuration of AGV flow path and time window constrained vehicle routeing strategy. Due to the complex and intricate nature of the manufacturing environment modelled in this study, solution through simulation analysis is the most desirable systems analysis technique. It has been used to give answers pertaining to vehicle fleet size, flow path design, buffer sizes, equipment utilization, evaluation of control/dispatching rules, establishing routeings etc.

Planning the capacity requirement of a material handling device for a manufacturing system has become a significant as well as complicated task. A plan that aids in determining the optimal number of vehicles required to provide a given level of transport service for a specific manufacturing scenario must begin by identifying how an AGV spends its time in the system. A complete vehicle journey for the purpose of a load transportation task can be viewed as comprising of the following activities — loading/unloading, loaded travel, empty travel, idle wait and blocked delay. An analytical modelling strategy is proposed in the present work as a screening device for use prior to a follow-up simulation study in determining the required number of vehicles. It involves computation of load transfer and transport times from given job parameters as the first step. One of the most studied aspects of an AGVS operating behaviour is the empty vehicle travel which is difficult to predict accurately due to inherent randomness of an FMS. Many research and empirical approaches to estimate empty vehicle travel have been discussed in this work and an approximation methodology has been developed. It entails formulation of a mixed

integer programme with an objective of minimising empty trips. The constraints are in the form of upper and lower bounds placed on the total number of empty trips starting from or ending at a load transfer station. The phenomena of vehicle waiting idle for a load transportation task to emerge and remaining in a blocked state due to traffic congestion have also been discussed. Load sensitivity analysis for various models has been performed by varying the rate of arrival of jobs into the system. A criticality index of material handling resource has been defined as the ratio of average processing time of a unit load to its average handling time. The results of the various models are then compared by varying this criticality index. From the foregoing analyses, an initial estimate of AGV fleet size is obtained which is then validated through computer simulation experiment of a hypothetical test facility. The simulation results indicate that the different models either under-estimate or over-estimate the actual number of vehicles required in the system. The proposed model, though under-estimates the minimum AGV requirement, yet provides results which come closest to the simulation results. Hence, it can be used as an analytical tool prior to the simulation phase of AGVS design.

Flow path layout of an AGVS affects total distance travelled by vehicles and consequently the fleet size required. It also has impact upon operating performance of the system due to traffic congestion induced in aisles. Configuring the flow path for an AGVS involves addressing issues such as flow path layout (unidirectional, bidirectional, multiple lanes, single loop, multiple non-intersecting loops), location of load transfer stations and traffic intersections, location of battery charging areas, vehicle parks, sidings and their holding capacities, traffic intensities in aisles, sizing of control zones, stops within zones, check zones, bypasses, etc. No research work has been reported in the the literature pertaining to the configuration of an AGVS flow path along the lines of a mixed (hybrid) uni/bidirectional flow mode. A heuristic methodology has been developed in the present work for this purpose. The given unidirectional flow path layout and a material flow intensities among various processing centres are taken as input information to this technique. Subsequent mixed uni/bidirectional flow path designs are obtained by considering a multiplicative function of material flow intensities between any two centres. The highest

such product indicates that that path is a strong candidate for being configured as bidirectional. The heuristic has been applied to the test facility and various alternate flow path designs are obtained. Simulation is then performed with an aim to compare the productive potentials of the facility when it is operated on either unidirectional, or hybrid uni/bidirectional, or all-bidirectional flow path design alternatives. The benefits of bidirectional flows over unidirectional counterpart are significant in terms of system throughput rates and optimal AGV fleet sizes. The decision related to location and capacity planning of vehicle buffering zones is also addressed.

Vehicle dispatching is a major part of system management. Dispatching strategy is a set of rules that have to be followed while prioritizing processing centres requesting the service of a vehicle for material pickup as well as while deciding on which vehicle to choose for a particular transportation task assignment. The rules are used for determining the sequence in which various routes will be visited. The selected control measures by which vehicles are assigned tasks can affect material flow, buffer storage requirement, machine and vehicle utilization. Various heuristic dispatching rules applicable under different shop operating conditions have been discussed. These rules include source driven (push type) and demand driven (pull type) vehicle initiated rules, work centre initiated rules, traffic rules at intersections, and job scheduling rules. The likely effects of these rules on the performance of the FMS are postulated. Shop locking phenomenon, which is an important operating behaviour of a system, has been discussed for its causes, repercussions, and remedies. The scope of the present work is a simulation study of the test facility. The aim is to make a comparative throughput performance evaluation of various source driven (push type) and demand driven (pull type) vehicle initiated dispatching rules. It is also demonstrated how the vehicle dispatching problem and its associated resolution technique can help in evaluation of buffer space requirements at each centre.

The problem of vehicle route planning consists of selection of a unique route for any given vehicle mission, in such a way that the vehicle reaches its destination using the shortest defined path. The main criterion of static path planning approach to this problem is to dispatch a vehicle by assigning it to the route associated with the minimum distance to its destination. Thus, the single objective function in such an

approach is to minimize the distance travelled by the vehicles. The probability of track congestion and vehicle blocking in an AGVS using static path planning is very high since the same optimal routes are taken regardless of the traffic conditions on the tracks. Such a system offers very little flexibility. On the other hand, dynamic approach has multiple objectives and constraints, and takes into account forecasting traffic status in each aisle in order to avoid congestion. The exact travel route is not known ahead of time until the journey is fathomed. Under this approach, a selected route is only tentative and is subject to revaluation every time the vehicle arrives at a node. A new path could be selected as a result of the revaluation. This form of path planning offers a very high degree of flexibility, operates in a real-time environment, and has potential application in conjunction with free ranging vehicles. A semi-dynamic routeing strategy based on time window constrained vehicle routeing has been proposed in the present work. Reserved time windows are placed on nodes indicating sequential crossing of nodes by the respective vehicles. Free time windows represent empty time slots available for vehicles to cross the nodes. Similarly, time windows representing direction of traffic flow are placed on the bidirectional arcs. Based on these time windows, Dijkstra's algorithm is applied to find the minimum blocking fastest route between any two locations. This route planning approach has been implemented on the different flow path alternatives obtained from the AGVS flow path design discussed earlier. The simulation study demonstrates that as the degree of bidirectionality of the AGVS network increases, vehicle blocking time also increases if a static route planning approach is adopted. However, if the proposed routeing strategy is employed, there is a considerable reduction in vehicle blocking time and shop throughput rate is significantly improved.

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Chapter 1

Automated Guided Vehicle System

1.1 Introduction

Manufacturing industry is undergoing perpetual changes during this last quarter of the twentieth century. To a large extent, these changes are a direct consequence of the "hard and fixed" automation which has progressively moved to "flexible and programmable" level through computerization. The discrete manufacturing industry is witnessing a tremendous spurt in the market need of customized products of high quality and at shorter lead times. This is forcing the industry to pattern its manufacturing style along flexible manufacturing system (FMS) lines. The focus is to seek maximum benefits obtainable from the flexibility concept of the FMS.

Groover (1987) defines FMS as a manufacturing system which consists of a group of numerically controlled (NC, CNC, DNC) machine tools connected by an automated material handling system (MHS) under computer control and set up to process a wide variety of different parts with low to medium demand volume. The ability of the host computer to take instant actions against changes within or outside the system, coupled with the versatility of the CNC machine tools and efficient MHS, gives the FMS its much acclaimed flexibility with regard to production requirements, while preserving the economies of scale of mass production.

At the core of an FMS is an automatic MHS. To a certain extent, the flexibility of the FMS results from the capability of its automatic MHS to accept parts in random order and in different volumes. The move towards increasing productivity has augmented the role of automated material handling. A flexible MHS (FMHS), besides meeting its primary objective of moving the right materials to the right place at the right time, must also be able to integrate with computer controlled manufacturing and distribution systems of all kinds. In fact, without integrated material handling, many of these modern manufacturing systems would remain islands of automation. In order to exploit the capabilities of an FMS it is equally necessary to use an efficient FMHS. An FMHS physically unifies all mechanical entities of an automated factory into an overall cohesive, co-ordinated plant function. A fully integrated FMHS can control the work-in-process (WIP) on the shop floor. Excessive WIP stock is a major cause of high manufacturing costs (Hartley 1984).

Of late, automated guided vehicle system (AGVS)[1] has emerged as the most promising FMHS in an FMS. The Material Handling Institute (1980) describes an AGVS as a system featuring battery powered, driverless vehicles with programming capabilities for path selection and positioning. Automated guided vehicles (AGVs) are seen as the ideal device for integrating process automation and as a way to achieve non-synchronous transport in assembly systems. With AGVS, changes in production volume or product routeing can be easily accommodated by simply reprogramming the paths to be taken by the vehicles. The system can be reconfigured more easily to accommodate changes in production volume, product mix, product routeing, or equipment interface requirements than is possible with most other MHSs. In a computer integrated manufacturing system (CIMS) environment, AGVs, with their communication protocols, have proved as the most efficient integrators and bridges of isles of automation.

[1]The "system" in the acronym AGVS has been used throughout this thesis to mean the total operating environment surrounding the AGV, rather than the vehicle itself. Thus, the material handling aspects of the system, and not the technical design considerations of the vehicle, form the scope of the system.

1.2 AGVS components

An AGVS has the following four main components.

1. The independently addressed and computer controlled vehicles of different capabilities and capacities.

2. The guide paths along which the vehicles move in loaded or empty condition.

3. The controls which direct and monitor system operations including feedback on moves, inventory, and vehicle status.

4. Interfaces with other computers (such as mainframe host computer), and systems (such as automated storage/retrieval system (AS/RS), or another FMS) (Eastman 1987).

The four components of AGVS are discussed below.

1.2.1 The vehicle and its guidance

AGVs are unmanned electronically guided vehicles generally under the control of a computer, that can automatically perform load pickup and delivery activities and seek the path from one location to another within the system. They are thus computer dispatched variable path equipment for material handling. They can be considered like mobile robots in moving frames of references, and as the discrete carrier components of a computerized integrated structure of a material flow system (Mehdian and Bera 1988). They are the means of transporting goods around a factory equipped with the latest developments in production technology by providing a smooth flow of goods which can be changed to accommodate the varying needs of manufacturing process as well as new product planning. The co-operating robotic vehicles can be programmed to load, unload, start, stop, accelerate, decelerate, block and select travel paths, and all without human intervention. Flexibility is the key in AGV based MHS. It is this characteristic that gives AGVs a prominent role to play in the development of automated factories of today and future.

Versatility, flexibility, and intelligence of AGVs allow for the integration of transportation, storage, and automated production processes by a direct computer control. This integration is the key to CIMS. McGinnis (1987) claimed that AGVs possess, to a larger extent, the following transport flexibilities — traffic flexibility, route flexibility, path flexibility, load flexibility, and change flexibility.

AGVs can do more than reduce labour content in manufacturing, they are also capable of increasing machine utilization by ensuring an uninterrupted flow of material on the shop floor. Besides contributing to precise control of inventory and production, the AGVs provide safe, consistent handling of the parts. Factors which have caused AGVs to become chief integrators in a CIM environment are advances in AGVS controls, advances in AS/RS controls, changeover of many machine tools to CNC systems, and the demand for productivity, diversity, and quality. The extensive integratibility of AGVs makes the concept of integrated workstations realizable.

■ *Types of vehicles*

Various major types of commercially available vehicles are described below.

Tugger can be used to pull or tow trailers (hand pallet trucks, custom trailers, bin trailers, flat beds) when large volumes/weights of material are to be moved over greater distances. Its usual applications involve moving raw material from storage to production areas, and finished goods from production areas to distribution warehouses.

Unit load carrier is equipped with a deck to carry on-board an individual load. It is an efficient means of horizontal transportation between hardware intensive material handling subsystems. AGV unit load application usually involves specific mission assignments for individual pallet movement. It can move high volumes of material over moderate distances, linking other automated subsystems in a totally integrated facility. It is a popular choice in applications integrating conveyors and AS/RS. It is quite versatile and can be used in wide variety of situations within warehousing and distribution systems, as

well as within manufacturing areas. Automatic load/unload capabilities and bidirectional movement can be provided.

Pallet truck is designed to transport palletized loads to and from floor level, eliminating the need of fixed load stands. It is generally used in distribution functions. It requires broader path layout.

Fork truck is a pallet truck with pallet lifting capability. It is used when multiple level AS/RS is a component of the FMS or when docking stations are of much different heights. It can stack loads in a rack.

Light load carrier is designed to move lighter loads (small parts, baskets, totes, supplies, mail, etc.) over shorter distances and in areas with limited space. Its applications involve electronic fabrication, small assembly shops, parts kitting, and office work. It is usually manually loaded/unloaded.

Assembly vehicle can be used as the basic move mechanism of an assembly line such as one for automobiles. It scores over hard assembly lines in terms of lower costs, ease of installation, flexible and programmable line paths, and variable speed and dwell intervals.

Robo vehicle has a robot installed on an AGV. This gives the robot mobility it lacks and the AGV the flexible manipulator it lacks. The functions of robot can include from simple loading/unloading to as varied as arc welding (Clayton 1983).

Guidance principles

There are several methods of guiding a vehicle on its path. They are discussed below.

Wire guidance is based on the principle of electromagnetic induction. A wire embedded in floor emits an AC signal (upto 40V, upto 400mA, and 5–35KHz) that produces a concentric electromagnetic field around the wire (Vosniakos and Mamalis 1990). The AGV carries sensors that detect this magnetic field. If

the vehicle deviates from the guide path, the AGV's on-board microprocessor directs action to return the vehicle to the guide path. Magnetic guidance is almost maintenance free. It can be used in harsh industrial environments with very high uptime.

Optical guidance uses an ultraviolet light which illuminates a fluorescent dye painted on the floor or on tape laid on floor. Photosensors detect the fluorescence and operate in a similar way to the scanning coils. These vehicles are used in clear environments of offices, or assembly shops. They have low installation costs and routes can be changed easily.

Free ranging AGV also called self guided vehicle (SGV), is not confined to follow a specified path, but can move freely by employing special navigation and guidance techniques (Premi and Besant 1983, Walker *et al* 1985, Dunn 1987, Drunk 1988, McGillem *et al* 1988, Van Brussel *et al* 1988). Several of the popular methods used for navigating vehicles include dead reckoning, optical stereoscopy, triangulation and line-of-sight targetting using infra-red lasers and position referencing beacons, inertial guidance, vision and ultrasonic imaging techniques (East 1988). Off-wire communication to and from the vehicle is accomplished through radio frequency or infra-red data transmissions. Dead reckoning is a vehicle guidance technique wherein, when AGV moves off the guide path and travels under computer control to accomplish loading/unloading task, the front wheel travel distance/rotation calculations are used to trace the vehicle back to its position on the guide path (Mechanical Engineering 1983). Many of the concepts of self guidance techniques are spinoffs of space and defence related research.

Because they rely on virtual paths rather than fixed routes, free roving AGVs possess a degree of flexibility compatible with the machining systems they serve, since routes can be simply changed by making appropriate changes in their software, that too in real-time while they are in motion. Route planning, vehicle dispatching and scheduling can be made more dynamic and adaptive to system states. They are cost efficient and ideal for harsh environment.

However, additional complexities arise in implementation of such a dynamic and adaptive system.

■ *Applications*

Technological developments may have given AGVS more flexibility and capability, but market acceptance has really given it the application variety to allow it to expand into the standard accepted material handling system it is today. Significant improvements in the vehicle systems, combined with imaginative applications have expanded the capabilities of AGVSs. AGVs have been used in the following situations.

Warehouse: Some of the earliest applications of AGVs were in moving raw material in bulk over longer distances within the facility or outdoors, or in very large distribution systems where the runs were quite long. The AGVs are tugger tow vehicles. Loading/unloading is usually done by fork trucks. Fork truck AGVs are used to integrate multiple level AS/RS with MHS.

Assembly: AGVs are being used in flexible transfer lines involving assembly and fabrication work. They feature customized load carrying mechanisms. A robot on-board the vehicle enhances possibilities in AGV's functions.

FMS: AGVs are gaining wider acceptance as primary material handling equipment in an FMS. They can be used to transport raw materials from stores to palletizing stations, fixtures and pallets from stores to palletizing stations and back after depalletizing, palletized workpieces among work centres, tools from stores to tool setting stations and to work centres, swarf and maintenance material, and even personnel.

1.2.2 Interfacing of AGVS with other subsystems

An AGV based MHS interfaces well with and complements other components of FMS such as AS/RS, loading/unloading stations at CNCs and work centres, process control equipment, and shop floor control system. The interface may be through

the host computer, although it is more efficient to use a distributed data processing network. Vehicles must align precisely for the purpose of docking with the given transfer station before load transfer can be achieved. Whenever a vehicle automatically transfers a load, a method of "handshake logic" must be employed wherein the vehicle or the system controller verifies either the presence of an empty slot before unloading, or the load on the stand before loading. The stopping accuracy of an AGV ranges from ± 0.25mm for machine tool interface to ± 6.00mm for an AS/RS (Eastman 1987).

"Opportunity charging" implies making use of vehicle stops at load transfer stations to connect the vehicle batteries to a charging circuit. It increases the uptime of a vehicle.

Load transfer between an AGV and a load pickup/delivery station can be accomplished in many different ways — manual, automatic coupling/decoupling of trailer train, power roller/belt/chain, power lift/lower, power push/pull, fork lift truck, hand pallet truck, crane, automatic transfer equipment, and shuttle transfer (Koff 1987). Automatic loading/unloading can be programmed. Where there are more load transfer stations than vehicles — usually the case in FMS — it is most economical to incorporate the loading/unloading mechanism on the AGV. In some cases, the AGV is equipped with spaces for two or more pallets.

The function of a part retrieval mechanism is to retrieve a particular part from among those which are present in a part buffer for the purpose of loading it onto an AGV. Sophistication in this mechanism directly dictates the choice of vehicle dispatching rules to be used. The two types of mechanisms are the following.

Sequential: It allows to retrieve only that part which is at the head of the buffer queue. Thus, a vehicle dispatching rule which prioritizes the parts present in the queue would fail to function with this mechanism,

Direct access: Any part from the queue can be retrieved regardless of its location in the queue.

1.2.3 AGVS controls

In addition to the aforementioned guidance, controls of an AGVS handle route selection, manage traffic, communicate remotely to vehicles, and interface with controls of other subsystems. Augmented control capabilities along with improved on-board diagnostics have made the AGV more reliable means of handling material than ever before. The three levels of AGVS computer control systems are described below.

Microprocessor is a small computer usually placed on-board the vehicle. It is programmed to perform a limited number of functions including navigation on the guide path, and operation of automatic loading/unloading mechanism. Microprocessor of an intelligent vehicle can also handle path planning for the vehicle.

System controller also called supervisory or traffic or transport controller, is a mini computer that handles dispatch-instructions to the vehicles and their route planning, and collects information on vehicle movement and inventory status on a real time basis. Its function is to manage the vehicle system in an organized and coherent manner.

Host computer is the organization's central mainframe computer that issues overall production plans to the shop floor.

A strong trend in today's FMSs is to keep intelligence at the lowest possible level of the syste hierarchy and as independent as possible from the host computer as opposed to a centralized control (Lindgren 1985, Koch 1988). In this context more and more computer power is found on the vehicles themselves (smart or intelligent vehicles) or in the control elements installed on the shop floor (smart eyes and smart floors). The decentralized approach to vehicle control deploys AGVs which act as autonomous active bodies planning independently their own global and/or local paths in the presence of fixed and moving obstacles. The approach is more meaningful in the context of free ranging AGVs which navigate in virtual paths rather than physical ones. The decentralized control ensures a high degree of independency, and parallel

processing and execution of different modules, which are in agreement with real-time control requirements.

Intelligence built into the vehicle depends upon its sensory feedback system which is linked to the local condition monitoring system. There are several levels of automation at which an AGVS can be operated. The automation levels range from simple systems that use manual loading/unloading and manual vehicle dispatching, to totally automated systems that include automatic vehicle dispatching, load/unload, path selection, system interrogation, report generation, and tracking of vehicles and parts.

There are two types of steering control mechanisms generally used for AGVs — steered-wheel steer control (all-wheel steering) with phase detection type of guidance sensor, and differential-speed steer control (differential steering) with amplitude detection type of guidance sensor. Thelatter has excellent guidance tolerance along the guide path, and is widely used. Travelling speeds of AGVs are in the range of 30–60 m/min for most types of vehicles used in machine shops. There are two approaches in the context of a vehicle negotiating guide path decision points (convergence and divergence points in the guide path) — frequency select method, and path-switch select method. The former has low maintenance costs. Communications at the lowest level is through electromagnets, permanent magnets, infra-red transmitters/receivers, miniature reprogrammable transponders, etc. At high level communication can be discrete through inductive or optical means (infra-red, photocells, LEDs), or it can be continuous on radio frequency.

System management includes the development of all policies necessary to control each vehicle in and at any possible situation. Path planning for an autonomous AGV refers to its ability to sense the environment and navigate through it. Traffic control and safety management is a system or vehicle ability to avoid collisions with other objects including other moving vehicles. The following two methods are used for safety management (Miller 1985).

Zone control: Guide path is segmented into separate zones and only one vehicle is permitted to occupy a given zone at a time. It can be accomplished by three methods — distributed zone control, central zone control, and on-board

control.

Forward Sensing: The mechanisms for forward sensing include the following types — pressure sensitive emergency contact bumpers, automatic signals (flashing lights, audible tones), emergency buttons, object detectors based on sonic (radar) and optical (infra-red) radiations. Forward sensing is effective on straight sections and is often used in conjunction with zone control technique.

1.2.4 Benefits of an AGVS

Among the many advantages credited to the use of AGVs (Begert 1988, Kulweic 1984), the following are some major ones.

1. flexibility in routeing, instant reactions to variations in part demand, tool availability, partial machine shutdowns (exception or hot-handling), adaptability to a variety of facility layouts including hazardous and contaminated environments,

2. automatic loading/unloading capability of AGVs including accurate positioning, physical interfacing with other FMS components such as production facilities, storage and buffers, robots, etc., chief integrating link in CIMS environment,

3. tighter control over material flow, shorter lead times, increased productivity,

4. flexible and better use of floor space, no ceiling structure, good accessibility to production facilities,

5. rapid and simple installation, high reliability and availability, safety, efficient and paperless work environment, improved house-keeping, modular expandability,

6. more efficient use of personnel, lower labour costs, lower investment cost in vehicles and guide path (but control system and software are expensive), and lower operating costs.

An AGVS has its limitations too. A thorough economic feasibility study has to be conducted for its justification, since the initial investment in hardware equipment (vehicles, floors, computers, etc.) and system controllers is considerably high. Besided, skilled manpower resource is required for its operation and control.

1.3 AGVS environment

Design and operational control of an AGVS is a complex task. It needs an in-depth understanding of the operating environment within the scope of which an AGVS has to be designed, implemented, monitored, and controlled. Figure 1.1 is a schematic block diagram representing the operating environment of an AGVS. The issues relevant in AGVS design and operational control are highlighted in the subsequent subsections.

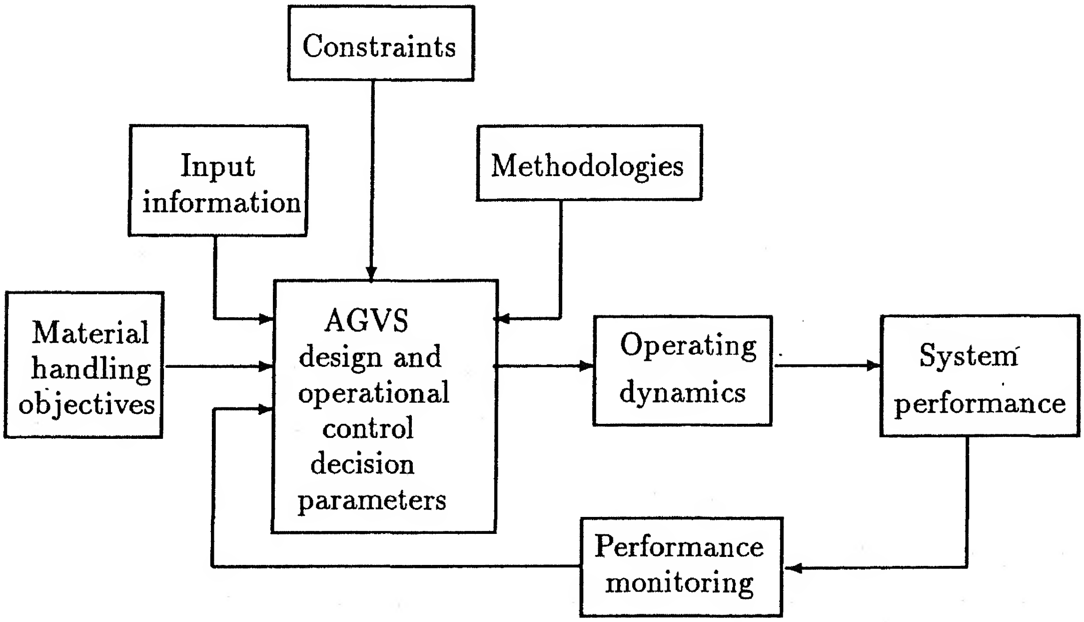

Figure 1.1: Operating environment of AGVS

1.3.1 Material handling objectives of AGVS

The material handling objectives of an AGVS constitute the requirement of transporting right material to the right destination in the right time resulting in maximization of shop throughput rate, reduction in WIP inventories, and increase in utilization rates of processing centres, vehicles, and guide path network.

1.3.2 AGVS design and operational control decision parameters

Although flexible in use, achievement of high performance for an AGVS is influenced by several design variables. Among these are the issues related to the following.

1. specifying appropriate guide path configuration, locating load transfer stations, designing vehicle buffering areas,

2. specifying the type and the size of required vehicle fleet necessary to adequately perform a given level of handling task,

3. specifying vehicle dispatching and routeing policies, and managing traffic,

4. specifying unit load size(s),

5. specifying central or local intermediate WIP storage capacity.

These issues are further discussed in subsequent paragraphs and literature relevant to them is reviewed in respective chapters.

■ *Configuration of guide path*

Guide path layout establishes the location and direction of vehicle travel. Guide path design is one of the most important issues in the overall AGVS design, since the performance of the system greatly depends on it. The main issues which have to be considered in the design of the guide path for an AGVS are the following.

1. flow path layout — unidirectional, bidirectional, multi-lane, single loop, multi-loop,

2. location of load transfer stations, traffic intersections — these represent the decision or communication points where two or more segments of the guide wire converge or diverge, battery charging areas, and vehicle parks,

3. sizing of control zones, stops within zones, and check zones, location and sizing of bypasses at load transfer stations,

4. routeing flexibility — consideration of alternate routes, minimization of vehicle idleness, traffic intensity in aisles, aisle space economy, etc.

One of the initial decisions to be made in the design of an AGVS guide path is to determine which mode of traffic flow pattern (unidirectional or bidirectional or other flows) is appropriate. Unidirectional flow design is more generally practised and justified because of the need for a much simpler control structure. Bidirectional flow system has been reported to be less frequently used in practice. It involves solution to three distinct problems — vehicle interference resolution at nodes, provision of vehicle buffering facilities along the layout, and vehicle traffic management along track segments. The vehicle buffering facilities can be provided at every node, or at a central location, or at selected intersections, and the design decision has to be taken accordingly. Issues which need to be addressed in the design of a multi-lane flow path include the number of virtual lanes of vehicle flow in each aisle, and the direction of flow in each lane. Design of a single loop flow path layout requires determination of an optimum routeing sequence of load transfer stations to be followed by the vehicles. When the vehicles operate in a multi-loop flow path layout, consideration of additional interfacing load transfer stations is imperative.

Analytical modelling of a guide path design can be approached in different ways based on initial assumptions made. These approaches include the following.

1. Design of facility layout, guide path layout, and location of load transfer stations.

2. Design of guide path layout, and location of load transfer stations based on an existing facility layout.

3. Design of guide path layout based on an existing facility layout, and location of load transfer stations.

Strict mathematical methods do not address the AGVS guide path design problem satisfactorily and hence empirical approaches are usually adopted. Moreover, rigorously tackling the problem involves addressing many more issues like the determination of the number of vehicles and the use of vehicle dispatching and routeing

rules. Thorough analysis is required to arrive at the right design of guide path layout for a particular AGVS application. Simulation technique is particularly useful in this regard. Simulation studies of various FMS layouts have proved that a substantial performance improvement in bidirectional over the unidirectional flow path design is usually to be expected in terms of FMS output. Fewer vehicles are required when switching to a bidirectional layout, and less space is occupied by the FMS facilities as a more compact arrangement is feasible. However, it is possible that processing centre buffers and vehicle buffer zones at a node are adversely affected, and in any case the results strongly depend upon the vehicle dispatching and routeing strategies used.

Determination of vehicle type and fleet size

Selection of the appropriate vehicle type(s) to be employed in an FMS has to follow an appropriate procedure normally based on a set of vehicle attributes and economics. Dahlstrom and Maskin (1981) compared the costs of different MHSs and suggested measures that can help designers to decide which option to choose. Schwind (1987) presented an AGV chart based on AGV characteristics and design features. Gunsser (1988) enumerated few important criteria for choosing a vehicle type. These include dimensions and weight of load and load container (pallet), frequency of transportation, kind of load transfer mechanism and transfer tolerances, and application. Shelton and Jones (1987) developed an attribute based selection model which differentiates between discrete attributes (bidirectional capability, etc.) and continuous ones (width, etc.). It then uses the additive form of the multi-attribute function, preference value functions in the form of analytical curves, and weighing factors according to the indifference method. The model assists the user in evaluating different requirements and provides a set of AGV types that meet the user's needs. The economic procedure for acquiring an AGV type, or the complete AGVS for that matter, is outside the scope of the present work.

Planning the capacity requirement of a material handling device for a manufacturing system has become a significant as well as a complicated task. The estimation of the number of vehicles is of paramount importance in AGV based MHSs and

requires a careful and detailed study, specially when AGVs are selected as the primary material handling equipment. The determination procedure has to take into account the operating conditions of the AGVS which include empty vehicle travel, vehicle blocking, etc.

■ *Specification of vehicle dispatching function*

Vehicle dispatching is a major part of system management. Dispatching strategy is a set of rules that have to be followed while deciding on which vehicle to choose for a particular transportation task assignment as well as for prioritizing processing centres requesting the service of a vehicle for material pickup. These rules are used for determining the sequence in which various routes will be visited.

In a manufacturing environment consisting of several processing centres performing different machining functions, a typical part or unit load visits several centres before its machining requirements are satisfied. A unit load continues to circulate in the shop between processing centres until it receives its last service. It is this transition of unit loads or parts that generate the vehicle dispatching problem in an AGVS. On completion of a load delivery task, the AGV is set idle or immediately reassigned a new task as the operating conditions dictate. If more loads are awaiting attendance at the same time in different stations, a decision to prioritize them is necessary. If, on the other hand, a number of vehicles are idle at the same time when a pickup task emerges, the appropriate rules have to be used to select a vehicle. When there is no pending task, an idle vehicle may wait at the load delivery station for a task to emerge, or it can be routed to a parking zone or a circulatory loop within the facility until requested for a task assignment.

■ *Vehicle route planning*

The problem of vehicle route planning consists of the selection of a unique route for any given vehicle mission, in such a way that the vehicle reaches its destination using the shortest defined path. There are two approaches to this problem.

Static planning: The main criterion is to dispatch a vehicle by assigning it to the route associated with the minimum distance to its destination. Same optimal routes are taken regardless of the traffic conditions on the track because the path between any two points in the network is predefined.

Dynamic planning: This approach has multiple objectives and constraints, and takes into account forecasting traffic status in each aisle in order to avoid congestion. The exact travel route is not known ahead of time until the journey is fathomed. Under this routeing approach, a selected route is only tentative and is subject to revaluation every time the vehicle arrives at a node. A new path could be selected as a result of the revaluation. This form of path planning offers a very high degree of flexibility, operates in a real-time environment, and has potential application in conjunction with free ranging vehicles.

With the path determination decision made, vehicle routeing further involves monitoring and controlling vehicle movement as it traverses its path. Path planning can be classified as the following two subproblems.

Global navigation implies planning a collision-free path for each AGV without considering other moving AGVs in the system,

Local navigation implies varying the velocities of the AGVs along their planned global paths so as to avoid collisions. Slight deviation from the global path in face of local monitoring conditions also comes within the purview of local navigation. This problem is transformed into a two dimensional time-space path problem to obtain a collision-free velocity profile.

▪ *Specification of unit load size*

Batch jobs continually arrive into a job-shop manufacturing environment. On arrival, the batch is broken up into unit loads. The number of unit loads that makeup a batch is a function of batch size, unit load size, and part characteristics. A unit load is transported and processed in the shop as a single entity. On completion of its last required operation, a unit load is transported to storage or warehouse by the an AGV. The AGVs also transport the unit loads within the shop.

The unit load size specification has a significant effect on the performance of an AGVS. Egbelu (1986) developed a method that permitted an AGVS designer to optimally and simultaneously specify the proper unit load size and the required number of vehicles that minimize the production cost. Larger unit load sizes are not always the correct solution to materials handling problem. Some other studies which emphasize unit load size specification have been conducted by Tanchoco and Agee (1981), Steudel and Moon (1987), Egbelu (1987c, 1993), and Mahadevan and Narendran (1992).

1.3.3 Operating dynamics of an AGVS

An important aspect in AGVS design is the characterization of the relationship between the AGVS design parameters and AGVS operating behaviour. Among the most important of the operating dynamics are:

1. empty vehicle travel,
2. variation in WIP storage queues,
3. vehicle blocking as a result of guide path contention,
4. shop locking phenomenon, etc.

The difficulty in describing the effects of AGVS design variables on operating dynamics arise from two primary sources. The first source is the interaction among the design variables themselves. Some examples of this type of relationship are as follows.

Not reqd

1. A poor location of load delivery stations in relation to load pickup stations may result in longer empty vehicle trips, thus necessitating a larger vehicle fleet size.
2. Vehicle dispatching rules that direct vehicles to the nearest load transfer station may contribute to guide path contention among vehicles at nodes close to work centres with high activity levels.

3. Additional vehicles can force an increase in the use of inefficient routeings as a result of congestion and contribute to increased average travel times.

4. Capacitated storage queues at work centres may decrease vehicle utilization and adversely affect vehicle dispatching strategies.

A second major difficulty arises in predicting the individual effects of design variables on system operating dynamics. No single element of operational control can be evaluated without understanding the effect it has on all other elements of operational control. The interactions and performance of the multiple decision variables are difficult to predict without detailed computational analysis. Usually, this detailed analysis involves computer simulation.

1.3.4 System performance and performance monitoring

System performance of an AGVS refers to the measured level of performance of the system when a specific combination of decision parameters is selected for implementation in a certain manufacturing environment. The decision-variable mix, when employed on the shop floor, manifests its collective impact in the form of operating dynamic behaviour of the system, which in turn dictates the overall system performance. Main indicators of the system performance are shop throughput rate and job mean flow time, processing centre utilization and WIP inventory levels, and vehicle utilization. Accordingly, the measures of the system performance can be classified as follows.

Job-based: shop throughput rate, mean flow time, mean tardiness, makespan, WIP inventory levels, etc.

Centre-based: mean utilization, WIP inventory levels, input/output buffer utilization of local and/or central storages, etc.

Vehicle-based: mean utilization, loaded travel time, empty travel time, waiting time, blocked time, etc.

Guide path network-based: mean utilization of aisles, traffic intensity in aisles and at nodes, capacity utilization of vehicle buffering zones, etc.

Designing and controlling an AGVS is an iterative procedure. The measured level of system performance is compared against the desired and intended standard level of performance for which the AGVS was designed in the first place. If there are any undesirable deviations in the output levels, they are rectified through a corrective action by varying composition of the decision-variable mix of the system. Thus, the procedure is iterative and consists of the following steps:

1. Defining the problem objectives, requirements, and constraints,
2. Developing an initial flow path layout,
3. Sizing of the vehicle fleet,
4. Refining the flow path layout,
5. Refining empty vehicle dispatching and vehicle routeing strategies,
6. Validating the design with simulation.

1.3.5 AGVS modelling

Scope of AGVS modelling is limited by the realities and underlying assumptions of the manufacturing environment which is being modelled. Each scenario has unique characteristics which are due to the nature of the entities or resources which it supports, including part types, processing centres, vehicles, and guide path network. Uniqueness of an FMS environment also stems from the desire and need to exploit various flexibilities of the FMS, for instance, product flexibility, volume flexibility, process flexibility, routeing flexibility, etc. Hence, the characterization of the environment and the depth to which the realities of the system are being reflected in the model will have direct influence on the complexity and modularity of the AGVS model.

▪ *Input information*

The modelling task of an AGVS requires certain amount of information to be fed as an input to the analysis of the model. The following pertinent information concerning various resources in the system is assumed to be available.

Material: part types, volume mix ratios, material flow matrix, job arrival rate, processing sequences and their respective probability density function, etc.

Processing centre: facilities layout (dimensional layout of aisles, location of load P/D stations — distance matrix), processing capacity (number of machines), processing time distributions, input/output buffer capacities at local and/or central storages, etc.

Vehicle: types, load carrying capacity, speed (loaded and empty — travel time matrix), availability factor, loading/unloading times, etc.

Guide path network: facilities layout (length and width of aisles), bidirectionality of aisles, control zone structuring, provision of vehicle buffering sidings at check points, vehicle parks and battery charging stations, etc.

Other resources which may require modelling effort include pallets, tools, maintenance supplies, etc.

▪ *Constraints*

An AGVS model is designed not only to attain the primary requirement of material handling, but also with other secondary considerations of, for instance,

1. material flow balance at load pickup/delivery stations,

2. workload balance among processing centres, vehicles, aisles,

3. shortest-route vehicle journeys, etc.

Such secondary objectives become the constraints within which the AGVS model is to be designed and optimized.

Methodologies

Various mathematical and analytical techniques have found application in the design and analysis of an AGVS model. These include linear programming (0-1 and mixed integer programming, transportation algorithms), branch-and-bound algorithms, dynamic programming, multi-salesman travelling path algorithms, queueing theory and Markov chains, networking (simple node-arc networks, Petri nets, neural nets), group technology heuristics, decision support systems (artificial intelligence, expert systems), fuzzy logic, etc.

Computer simulation has been a powerful technique both for designing an AGVS model and validating the design. It is an important tool used for monitoring and controlling the system performance, even before the implementation of the system.

1.4 Scope of the present work

The present work has been carried out with an objective of studying the interactions among some of the major decision variables of AGVS and evaluating their effect on system operating behaviour. The aim is to specify appropriate levels of design parameters and control strategies within the manufacturing scenario that will achieve an acceptable level of performance based on some shop performance measures. For this purpose, two design parameters — AGV fleet size and guide path configuration, and two operational control measures — vehicle dispatching strategies and vehicle route planning have been considered. The work performed revolves around these four main issues. The example presented in this study represents a typical production facility where installation of an AGV based MHS is required. The chapter organization is described below.

Chapter 2 details the AGVS application environment. It discusses the assumptions made in this study, enumerates the characteristics of the entities of an AGVS and presents modelling concepts of these entities. The salient features of a hypothetical test facility are also discussed.

The design issue related to the determination of AGV fleet size is discussed in Chapter 3. One of the most studied aspects of an AGVS operating behaviour is

the empty vehicle travel. It is this operating condition that influences most the process of fleet sizing. The inherent randomness in an FMS makes it difficult to predict accurately the amount of empty vehicle trip time. The chapter discusses several research and empirical models reported in the literature to estimate this time component. An analytical modelling strategy is proposed as a screening device for use prior to a follow-up simulation study in determining the required number of vehicles. The chapter concludes with the results and discussion of the simulation experiment of the FMS test facility.

The issue of AGVS flow path design is taken up in Chapter 4. The flow path layout for an AGVS is a vital decision in the overall system design. It directly influences AGVS operating behaviour in the form of vehicle contention for guide path and traffic blocking. A heuristic methodology is developed in the present work for configuring the flow path of an AGVS along the lines of a hybrid (mixed) uni/bidirectional flow mode. The heuristic is applied to the test facility and various alternate flow path designs are obtained. The chapter includes a case-study in simulation experiment of the FMS test facility. The aim is to compare the productive potentials of the facility when it is operated on either unidirectional, or hybrid uni/bidirectional, or all-bidirectional flow path design alternatives. The decision related to the location and capacity planning of vehicle buffering zones is also discussed.

Chapter 5 addresses one of the important operational control measures, namely vehicle dispatching strategies. Various dispatching rules applicable under different shop operating conditions are discussed. The likely effects of these rules on the performance of the FMS are postulated. Shop locking phenomenon, which is an important operating behaviour of a system, is discussed for its causes, repercussions, and remedies. The chapter is a case-study in simulation experiment of the FMS test facility. The performance effect of various dispatching rules is compared and discussed about. The measures of performance include system throughput rate and average queue levels at processing centres' buffers.

Chapter 6 deals with another AGVS operational control measure, namely vehicle route planning. It discusses the static and dynamic path planning approaches for

selection of a unique route for any given vehicle mission. A semi-dynamic routeing strategy based on time window constrained vehicle routeing is proposed in the present work. Reserved time windows are placed on nodes indicating sequential crossing of nodes by respective vehicles. Similarly, time windows are placed on bidirectional arcs representing the direction of traffic flow. Based on these time windows, Dijkstra's algorithm is applied to find the minimum blocking fastest route between any two locations. The simulation study of the test facility demonstrates that shop throughput rate is significantly improved by adopting this vehicle routeing strategy.

Chapter 7 concludes the main concepts and results of the present work. It also details the scope of further research work that can be taken up in this vitally important field.

Chapter 2

AGVS Modelling

The objective of the present work is to characterize an AGVS by studying the interactions among some of the important decision variables and their impacts upon the operating dynamics of the system. The application environment is described below.

2.1 Application environment

The production environment modelled in this study comprises of an automated manufacturing job-shop that is an FMS. Within the system are conceived various types of entities such as processing centres, guide path layout, parts, vehicles, etc. organized according to specialized functions. It is assumed that all the design and setup issues within the hierarchy of operations research problems in an FMS as suggested by Stecke (1985) have already been resolved. The set of part types which will be produced during the planning period are determined. The types and number of processing centres are known. Even though the important characteristics of an FMS are considered in the present work, some of the other typical FMS resources such as tools, pallets, fixtures, and their availabilities are not modelled. Allocation of these resources are assumed to have been made at the planning stage when the batching and loading decisions are made, so that it may be reasonable to assume the continuous availability of these types of resources. Furthermore, it is

assumed that the routeing of each part type is available before making any vehicle dispatching/routeing decisions. Information on processing, loading/unloading, and travel times are available. Pre-emption of job operations or vehicle trips is not allowed. Issues such as machine failure or down-time, scraps and rework, vehicle dispatch for battery changes, etc. are ignored. *(see at the bottom)

2.1.1 Job parameters

A dynamic job production system with capability to handle different classes of job types is assumed. Batch jobs continuously arrive into the shop for processing. The batch arrival process is described by specifying an appropriate probability distribution representing the arrival process of batches into the system. The rate of arrivals is driven by the parameter(s) of the specified distribution. The arrival of one job initiates the arrival of the subsequent job. On arrival, the job class is identified according to some underlying probability distribution. The job is then unitized as a unit load for transportation and processing purpose. The present work assumes that the batch size of an arriving job is unity and the terms job, part, item, workpiece, and unit load have been synonymously used. Depending on the job type, each unit load has one or more known machining route(s). A unit load leaves the shop on completion of its last required operation.

■ *Alternate process plans*

In an automated flexible manufacturing environment consisting of several processing centres performing various processing functions, a typical part visits some or all of the centres for its processing needs. Due to the versatility of the machines, the part can be processed in more than one possible sequence. This imparts flexibility in routeing a part through the system. The alternate routes of a part are taken advantage of when considering issues such as machine failure and workload balance. Since a part can be processed under multiple sequences, the actual material flow will depend on the operating behaviour of the system, such as variation in intermediate buffer levels. The material handling requirement under this scenario becomes more

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The solutions and results arrived at in the following chapters, after taking these assumptions into consideration, may serve as guidelines for the purpose of design and operational charaterization of an AGVS. Important entities of the system which have been modelled in

fluctuating and time-phased than under single process plans. Flexibility in the process plans (process flexibility) can be provided by varying the order of processes. Alternate routes (routeing flexibility) give AGVS the flexibility to choose between paths for delivery.

2.1.2 Processing centres and material movement

The modelling of processing centres and machining operations are macroscopic in nature. Detailed activities of a machining operation such as machine loading and unloading, movement of unit loads within the centre, selection of machining parameters (i.e., speed, feed, and depth of cut) are aggregated as part of the machining requirements. A processing centre is modelled as a multiple server queueing system as depicted in Figure 2.1. Each centre has a finite number of identical machines and unique input and output queues of parts. Only local part buffering capacity in front of each centre has been considered in this study and no provision has been made for a central part storage facility. Thus, a vehicle's movement is restricted between pairs of load pickup/delivery (P/D) stations of various centres. Material movement within a centre is taken care of by secondary means of material handling like robots, etc. Unit loads are delivered into the input queue of a centre at its delivery (D) station by AGVs. The queue is driven by a selected job dispatching rule according to which a job is selected for processing if any machine in the centre is idle. On completion of processing, the unit load is placed in the output queue at the centre's pickup (P) station, bound for the next centre, provided a space is available in the output buffer. Otherwise, the load cannot be downloaded and machine remains blocked. If all the machines of a centre become blocked, the centre itself is declared blocked. AGVs pick outbound unit loads, again according to some rule. The load P/D stations of a centre may be co-located or situated at different sites.

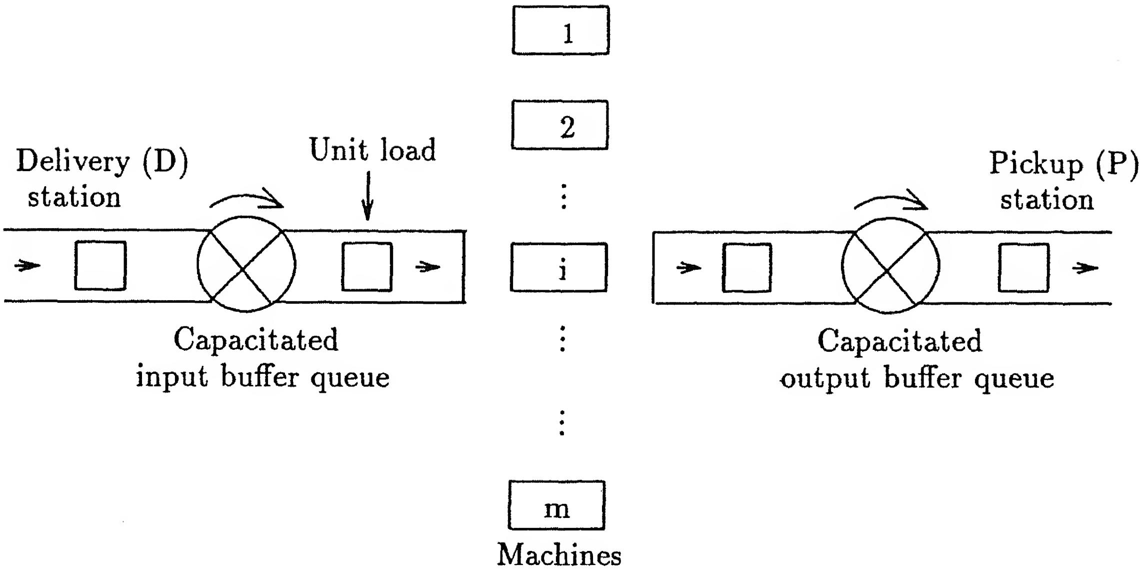

Figure 2.1: Schematic diagram of a processing centre

2.1.3 Guide path network

The layout of the guide wires constitutes the guide path network system. The consideration of the paths dictate the direction of traffic flows. Flow of traffic can be unidirectional or bidirectional. The guide path system is modelled as a network. The nodes of the network are the load P/D stations and the intersection points (crossings, merges, and diverges). These are depicted in Figure 2.2. The network arcs are the guide path segments between two nodes. An arc thus has a source node and a terminal node. No two or more arcs can have a common source and terminal nodes simultaneously. A unidirectional arc is uniquely identified by specifying the nodes that bound the arc. The arc specification also indicates the orientation of the arc. Thus, arc(i,j) = arc(j,i) for a bidirectional arc, whereas only one of the two can exist for a unidirectional arc. It is assumed that all arcs have vehicle buffers (sidings) at their terminal nodes and that the buffers are of adequate capacity to hold all the vehicles in the system. Furthermore, it is assumed that the time required for a vehicle to steer into and out of the buffer is negligible compared to the overall transit time required.

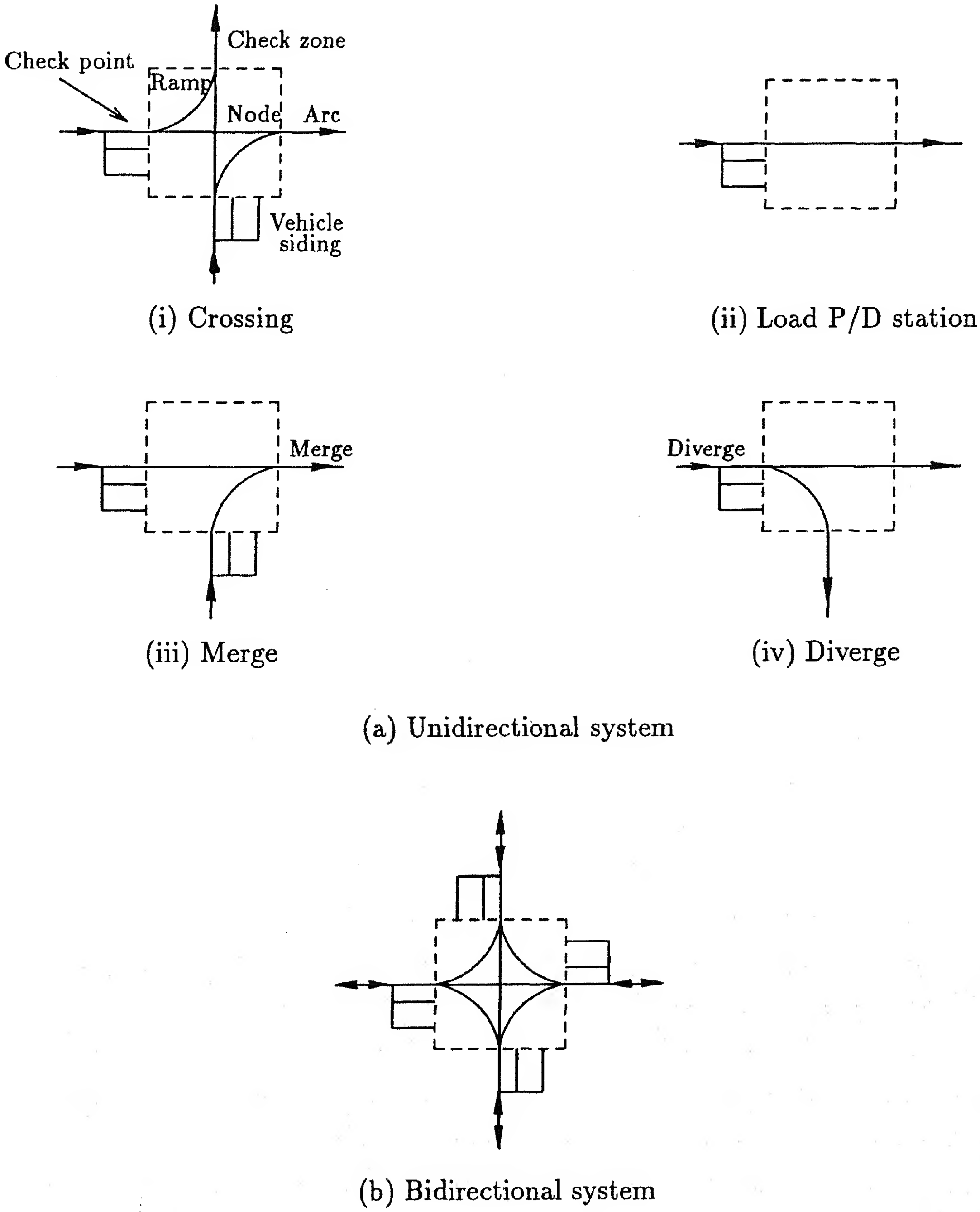

Figure 2.2: Schematic diagram of a node

Surrounding every node is an invisible check zone. The point where the check zone intersects with an arc of a node is the check point. The check points are essentially the decision points in the network while check zones are safety zones designed to ensure safe crossing of vehicles. No two vehicles can occupy the same check zone simultaneously. No sharp vehicle turns are allowed. All turns are through interchange ramps as shown in Figure 2.2. Crossing time of a vehicle through a check zone is assumed to be constant irrespective of the type of ramp it traverses through the zone. The time required to travel from one node to another depends on the distance between the nodes, the vehicle travel speed, and the occurrence of any blocking. When a vehicle is blocked, it is held in the siding at the check point of the node in question for some time until the traffic condition around the node improves to permit crossing. From discrete simulation view point, the movement of a vehicle from a source node to a destination node is modelled as consisting of discrete jumps from check point of one node to that of another. A minimum headway distance is assumed between two adjacent vehicles using the same arc in the same direction.

2.1.4 Vehicles

AGVs are considered to be the primary means of material handling in the present study. They move unit loads within the shop as well as from/to stores and warehouses. Unit loads and vehicles are the only entities that flow in the system. Part of the time, both entities flow as a single entity. This happens when a unit load is being transported by a vehicle. At other times, the two entities flow separately. This is equivalent to a vehicle travelling empty, or a unit load being processed at a centre or waiting in its buffers. Figure 2.3 illustrates the vehicle-unit load transport system. Thus, a unit load may be located in any of the four states, viz., at a centre being processed, in input buffer waiting for processing, in output buffer waiting for a vehicle, or on-board a vehicle. Simultaneous load transfers by two or more vehicles at the same station is not permitted. Transfer operations are undertaken sequentially by waiting vehicles on a First Come First Serve (FCFS) basis. On completion of the pickup activity, the loaded vehicle departs the P station if the next arc is not congested. Otherwise, the vehicle is held in place until the aisle is

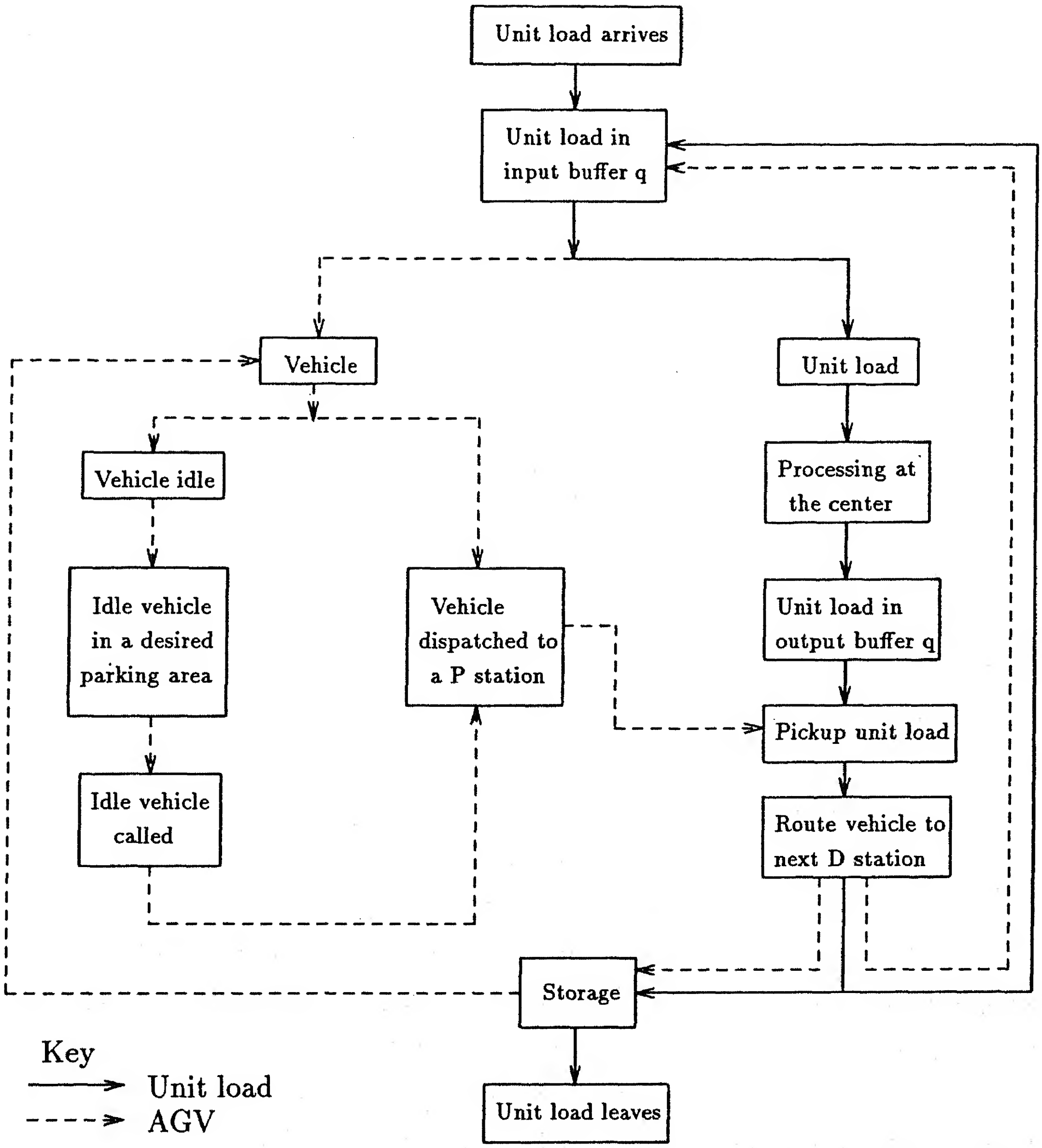

Figure 2.3: Vehicle-unit load transport system

cleared. On the other hand, on completion of the delivery activity, the vehicle is set free or reassigned a new pickup task. In the former case, the vehicle may be held idle at the same D station, or recirculated empty in the network, or dispatched to a vehicle park. Holding of a vehicle can take place at an intersection or a load P/D station.

All the vehicles are assumed to be unit load carrier type with bidirectional capability, and identical in terms of load carrying capacity (one unit load at a time), speed, and availability factor. They get their batteries charged while making stops at load transfer stations (opportunity charging).

2.2 A hypothetical illustrative test facility

The layout of a hypothetical FMS considered for illustration purpose is shown in Figure 2.4. It consists of six processing centres. The multiple recirculating loop pattern of unidirectional AGV guide path shown in the figure facilitates shorter vehicle routes from one point to another (Haines 1985, Vosniakos and Mamalis 1990). The layout is a modified version of tandem configuration (Bozer and Srinivasan 1989, 1991). There are at least three single loops meshing with each other ($PC1 \rightarrow PC6 \rightarrow PC1$, $PC2 \rightarrow PC3 \rightarrow PC2$, $PC4 \rightarrow PC5 \rightarrow PC4$), and one outer loop connecting all the six processing centres ($PC1 \rightarrow PC2 \rightarrow PC4 \rightarrow PC6 \rightarrow PC5 \rightarrow PC3 \rightarrow PC1$). P/D stations of each centre are co-located. Parts enter and leave the system through the receiving/shipping centre which has been numbered 1. Other data concerning the processing centres are given in Table 2.1. Currently there are three part types, with known volume mix, which are considered for processing. Each part type can be processed under multiple process plans with known probabilities. Job arrival pattern is assumed to be a Poisson process. Processing times of various part types at different centres are assumed constant. Routing data describing the flow of the shop are given in Table 2.2. Details about vehicle travelling time between various pairs of P/D stations, vehicle loading/unloading time, etc., are presented in Table 2.3.

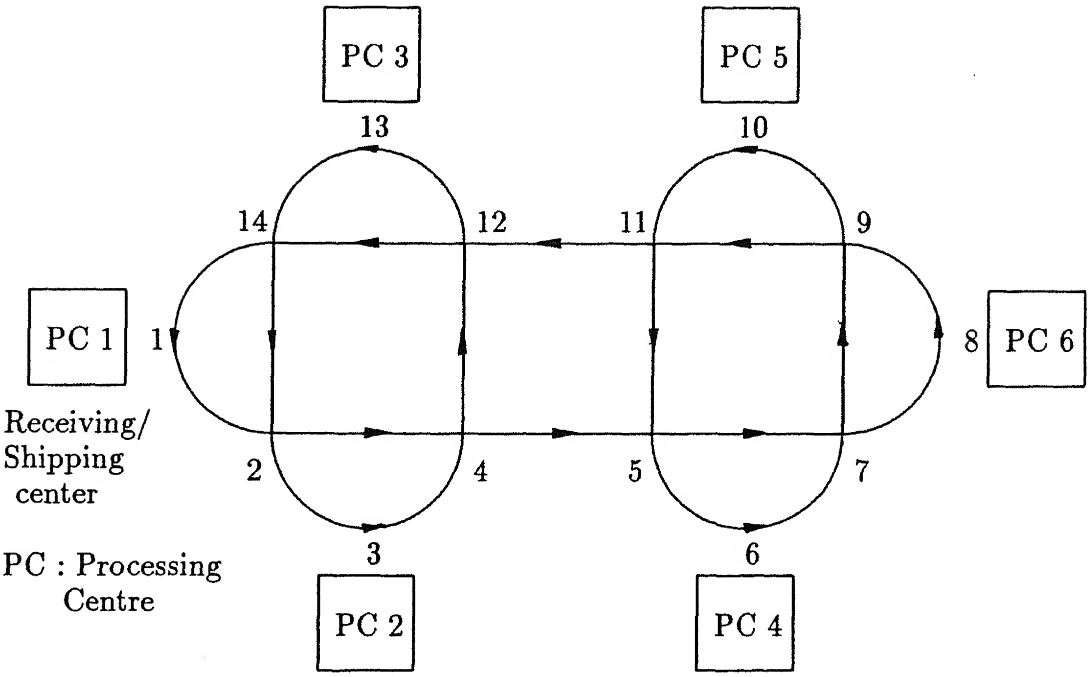

Figure 2.4: Layout of the illustrative FMS

Table 2.1: Processing centre data

Processing centre	Number of machines	Pickup/delivery station number	Buffer capacity[a] input	output
1	1	1	∞	∞
2	4	3	5	5
3	4	13	5	5
4	4	6	5	5
5	4	10	5	5
6	5	8	7	7

[a]Buffer capacities are considered for simulation purpose only.

Table 2.2: Job flow data

Part type	Vol. mix	Process plans No.	Prob.	Route (centre)	Times (min)
1	0.2	8	0.125 each	1, (2/3), 6, (5/4), 6, (3/2), 1	0, 12, 18, 15, 18, 12, 0
2	0.3	4	0.25 each	1, (2/4), 6, (5/3), 1	0, 17, 16, 17, 0
3	0.5	2	0.5 each	1, (2, 5) / (4, 3), 1	0, 18, 18, 0

Table 2.3: Vehicle travelling time (min) and other related data

	Centre	P/D point	To 1 (P/D 1)	2 (P/D 3)	3 (P/D 13)	4 (P/D 6)	5 (P/D 10)	6 (P/D 8)
From	1	1	–	1.5	3.5	3.5	5.5	4.5
	2	3	3.5	–	2.5	2.5	4.5	3.5
	3	13	1.5	2.5	–	4.5	6.5	5.5
	4	6	5.5	6.5	4.5	–	2.5	1.5
	5	10	3.5	4.5	2.5	2.5	–	3.5
	6	8	4.5	5.5	3.5	3.5	1.5	–

Vehicle travelling time through : a straight arc = 0.85 min
: a curved arc = 0.60 min
: a check zone = 0.15 min

Vehicle loading/unloading time at any P/D station = 0.5 min
Vehicle availability factor = 100 %
Length of planning horizon = 480 min

2.3 Methodology

The design and operational characterization of an AGVS presents difficulties due to the presence of multiple decision variables whose interactions and performance impacts may be difficult to predict without detailed computational analysis. Usually, this detailed analysis involves computer simulation. Randomness which is inherent in FMS results in complication of both design and evaluation efforts. As far as design is concerned analytical methods can be proposed using average quantities or mathematical distributions to represent real data. For evaluation purpose, however, simulation seems an inevitable solution. Analytical methods can facilitate extensive sensitivity studies needed to support a system-design effort. However, it is not possible to develop a significantly integrated and valid set of analytical models to produce results comparable in accuracy and detail with those obtainable through computer simulation. New automated manufacturing systems offer flexibility of manufacturing and handling, but they also present a new type of problem. This problem is that the operating policies and system dynamics can no longer be considered separately. The inability of an analytical model to predict accurately the levels of and variations in operating characteristics can undermine the utility and validity of the model. A mathematical formulation of the comprehensive model developed may be very large for any realistic system. The present work incorporates both the analytical and computer simulation techniques.

2.3.1 Analytical techniques

The principal technique used for analytical modelling of AGVS in the present work is mixed integer linear programming for the purpose of estimating empty vehicle travel time. Empty travel of vehicles is one of the most important operating behaviours of the system and many models and empirical approaches for its approximation have been reported in the literature. A new model in this regard is proposed in the present work.

Other analytical techniques used in the present work include development of heuristics for the purpose of configuring a hybrid uni/bidirectional flow path layout,

Many simulation languages and simulators are commercially available, e.g., GPSS, SIMAN, SIMSCRIPT II.5, SLAM II, WITNESS, PROSIM, ARENA, SIMPLE ++, etc. They have good modelling capabilities together with animation features. Nevertheless, a special purpose simulator written in C language has been developed in this work for the defined problem environment. The commercially available simulation packages require the problem to be modelled and descriptors to be oriented according to their own spsecific configuration and building blocks. The present problem, if attempted to be simulated using any of these languages has to be remodelled according to the requirements of the language, and this may pose some restrictions in the problem environment described. While the present problem can be simulated using any of these languages but with some restrictions, C language is chosen to simulate the system which allows all the features of the described problem environment to be incorporated. Furthermore, the severe requirement of comprehensive statistical analysis of the output results has discouraged the use of the popular simulation languages in favour of C which allows writing any statistical inferencing routine as may seem necessary. The data structures needed for the present problem include the use of linked lists for computationl efficiency and dynamic memory management. It is known that C language provides these features better than any other language.

With the above discussion in view, a discrete event oriented simulator is developed in C and implemented on HP-9000/850 computer system. Its salient features are described below.

and for time window constrained vehicle route planning.

2.3.2 Simulation

Due to the complex and interactive nature of the manufacturing environment modelled in this study, solution through simulation analysis is the most desirable system analysis technique. Simulation has been used extensively in practice for analyzing complex manufacturing and automated material handling environments (Phillips 1980). Characteristic quantities which can be monitored in a simulation of an AGVS are:

FMS centred throughput, utilization, buffer levels, etc.

Job centred flow time, makespan, tardiness, etc.

AGV centred utilization, idleness, empty travel, blocking delay, track utilization, etc.

Simulation is used in the present study to investigate the impact of various decision parameters on the system operating behaviour. It is used to give answers pertaining to vehicle fleet size, flow path design, buffer sizes, equipment utilization, evaluation of control/dispatching rules, establishing routeings, etc. *(see the left side page)

■ *Events and procedures*

Nine separate events are identified for the purpose of event oriented simulator. The interactions among these events are illustrated in Figure 2.5. The simulation process is stopped after certain specified simulation time. The final statistics regarding shop throughput, vehicle times, input/output buffers, etc. are then collected and results are reported. The events, together with major conditions to be checked and actions to be taken, are described below.

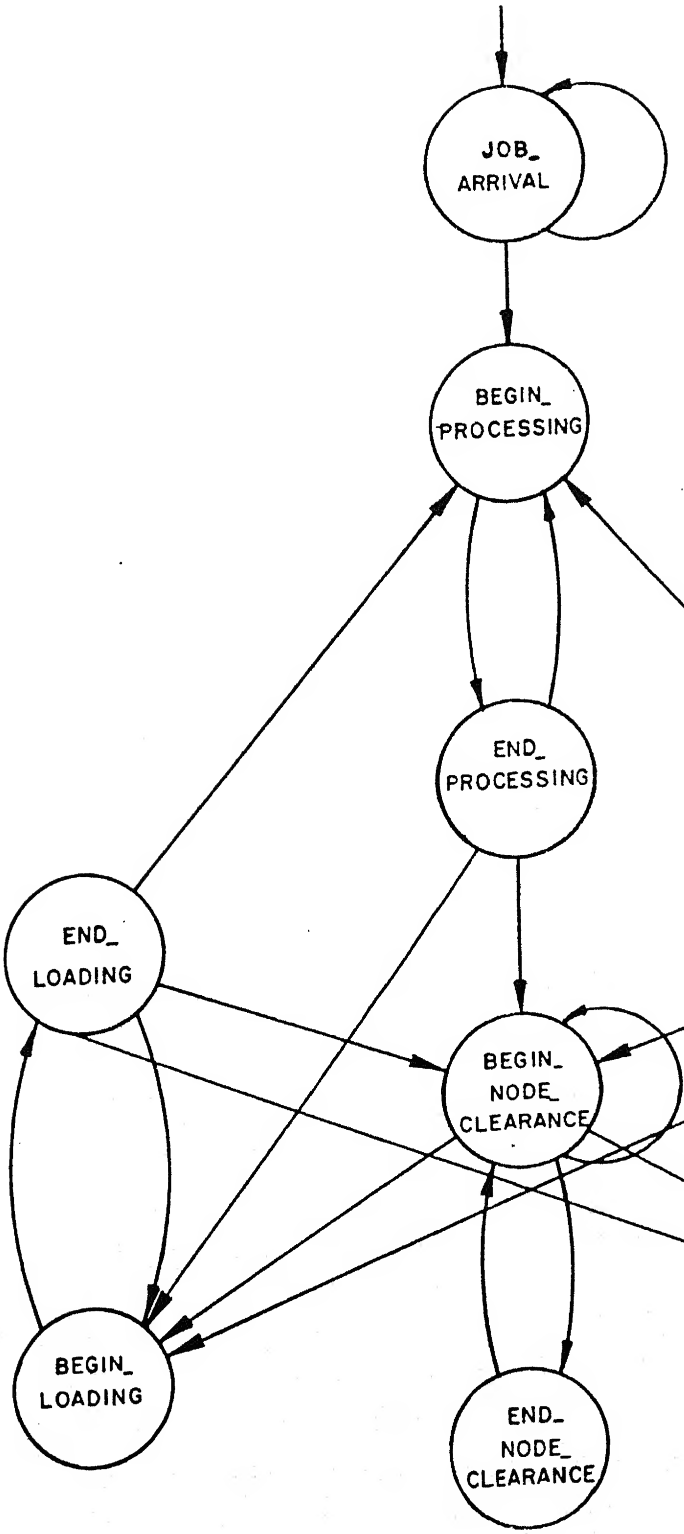

Figure 2.5: Event graph of the simulator

JOB_ARRIVAL: Job arrival into the system is driven by a Poisson process with a specified mean arrival rate. Each arrival of a job triggers the next arrival. The arriving job type is identified according to a specified probability distribution and the job is inserted in the input buffer queue of the receiving centre, the capacity of which is assumed to be infinite. If the palletizing machine in the receiving centre is free, the job is immediately scheduled for processing (palletizing operation in this case).

BEGIN_PROCESSING: Processing of a job at a processing centre is scheduled on FCFS basis. The processing time is determined according to the job type, and END_PROCESSING event is scheduled.

END_PROCESSING: The job leaves the system through the shipping centre if it has been processed for its last operation, otherwise a course of action is taken in order to decide the status of this job. This mechanism is shown in Figure 2.6. The subsequent events which can be triggered are BEGIN_PROCESSING, BEGIN_LOADING, or BEGIN_NODE_CLEARANCE.

BEGIN_NODE_CLEARANCE: The event is triggered either when a vehicle arrives at a node, or when a vehicle has crossed the node and another vehicle is waiting to clear the node, or when loading or unloading operation has been accomplished at the node and the respective vehicle intends to move away from the node. Depending on each individual case, a suitable course of action is taken. Subsequent events that can be triggered include END_NODE_CLEARANCE, BEGIN_NODE_CLEARANCE, BEGIN_LOADING, or BEGIN_UNLOADING. The scheme of tackling this event is shown in the flow chart of Figure 2.7.

END_NODE_CLEARANCE: The node is declared free for clearance by other vehicles. If another vehicle is awaiting clearance at the same node, BEGIN_NODE_CLEARANCE event is scheduled. BEGIN_NODE_CLEARANCE is also scheduled at the next node where the vehicle which has just crossed the node in question, will reach.

BEGIN_LOADING: This event signifies beginning of the activity of transferring a unit load from the output buffer of a centre onto the vehicle. It triggers

END_LOADING event in turn.

END_LOADING: The event triggers, in turn, BEGIN_LOADING or BEGIN_UNLOADING if another vehicle is awaiting loading/unloading at the same node. If the centre has a blocked machine, then that job is downloaded onto the output buffer and BEGIN_PROCESSING is triggered if a new job is present in the input buffer. The vehicle which has been loaded seeks to move out of the node, hence, BEGIN_NODE_CLEARANCE event is triggered if the node is available for crossing. The flow chart is shown in Figure 2.8.

BEGIN_UNLOADING: The event is analogous to BEGIN_LOADING.

END_UNLOADING: The event triggers, in turn, BEGIN_LOADING or BEGIN_UNLOADING if another vehicle is awaiting loading/unloading at the same node. If the centre has an idle machine, then BEGIN_PROCESSING is scheduled. If the vehicle is assigned a new pickup task, then BEGIN_NODE_CLEARANCE is scheduled. The flow chart for this event is shown in Figure 2.9.

Several modular procedures are written in order to take suitable courses of action under different events. These include the following.

Insertion of an event in the event list, of a job in input/output queues, of a vehicle at a nodal or loading/unloading queue, of a vehicle in a siding or in an arc.

Deletion of the same type as Insertion described above.

Finding next arc for a vehicle to enter, route of a vehicle (using Dijkstra's algorithm), destination of a job, next job to be picked up by an idle vehicle, idle vehicle for pickup of a current job, etc.

▪ *Random number generator*

An ANSI C version of a prime modulus multiplicative linear congruential generator (PMMLCG), as reported by Marse and Roberts (1983), is used for generating random numbers. The source code of this generator is presented in Appendix A. The generator produces 100 streams of random numbers, each stream of length 100,000.

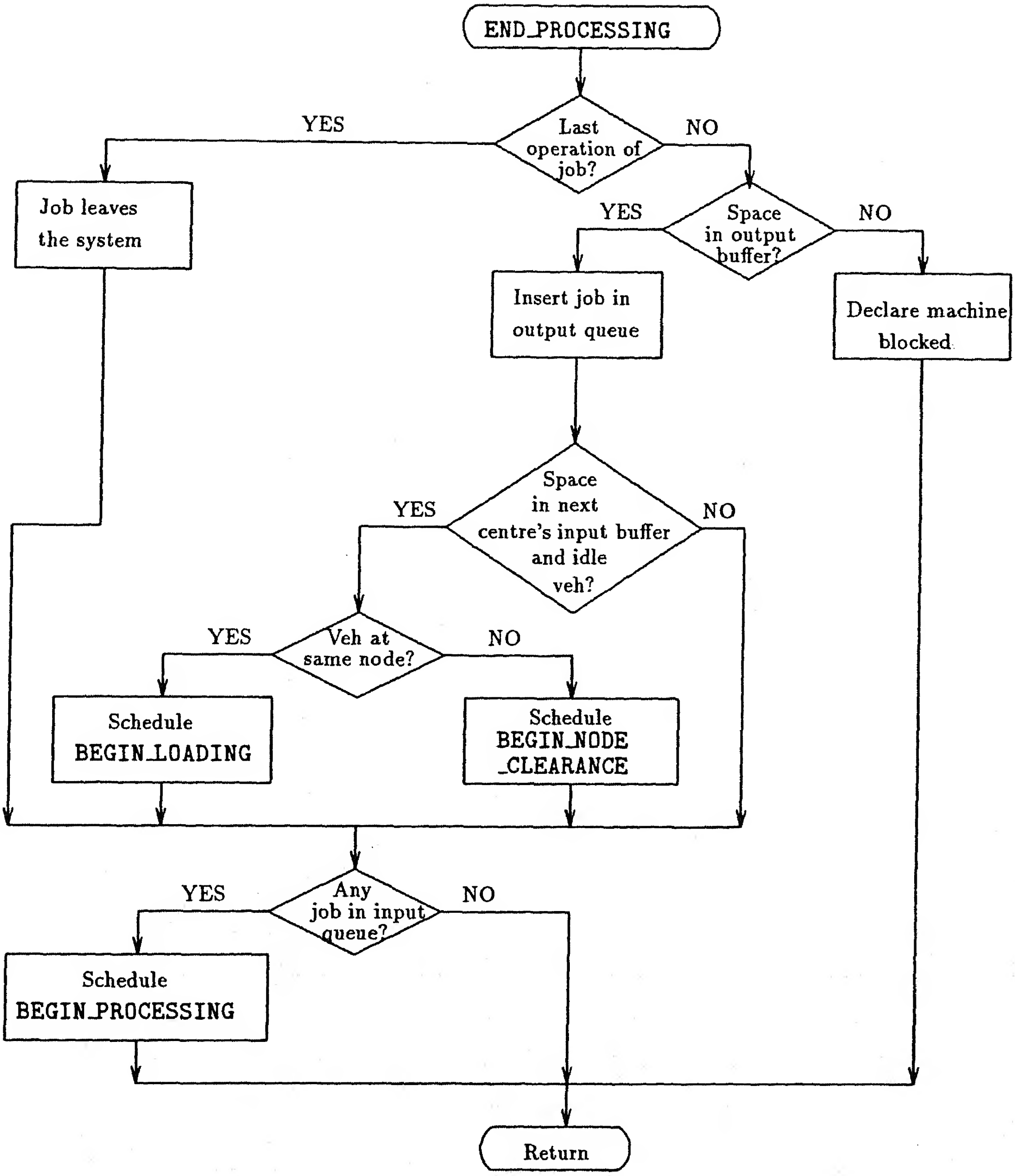

Figure 2.6: Flow chart for the event END_PROCESSING

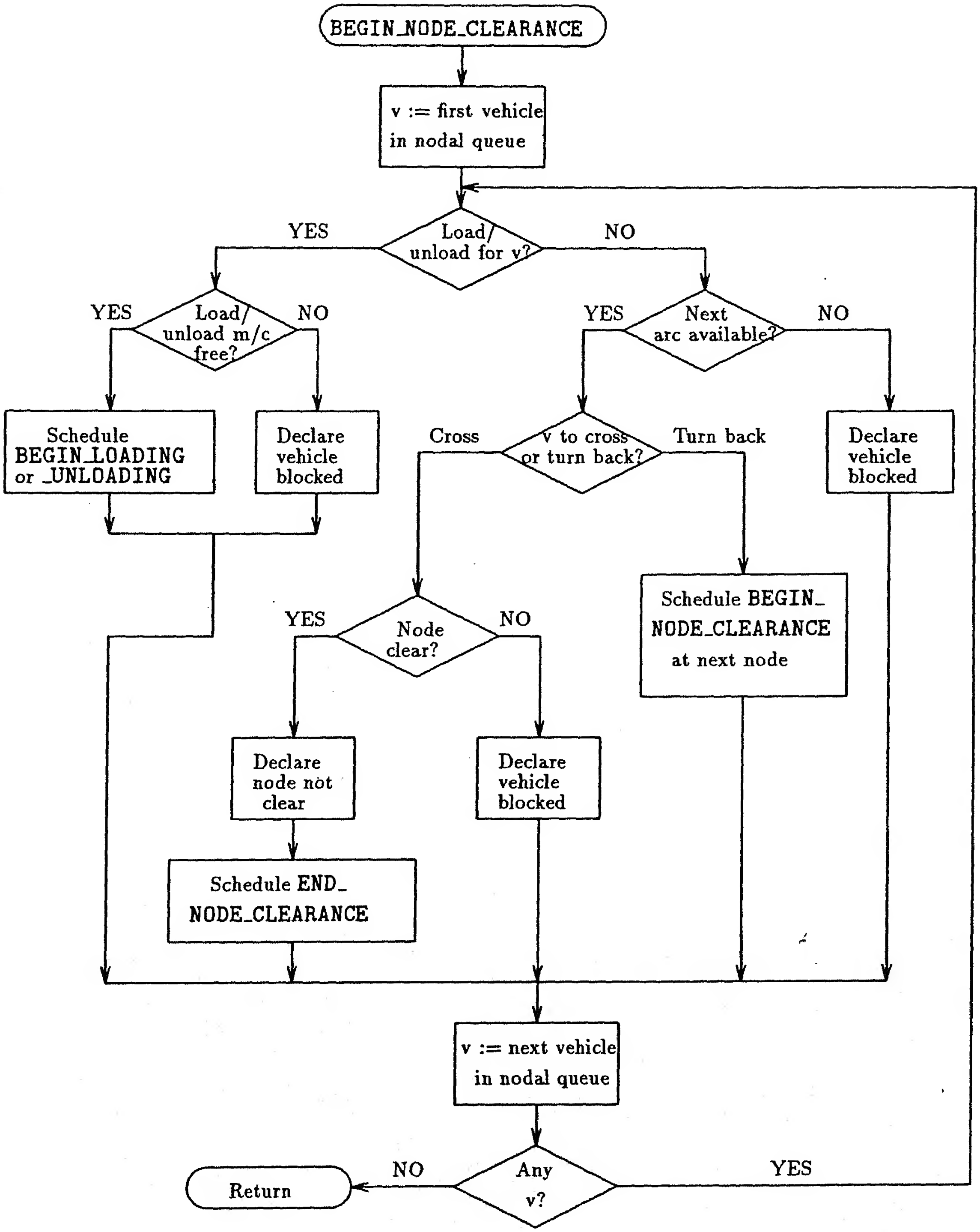

Figure 2.7: Flow chart for the event BEGIN_NODE_CLEARANCE

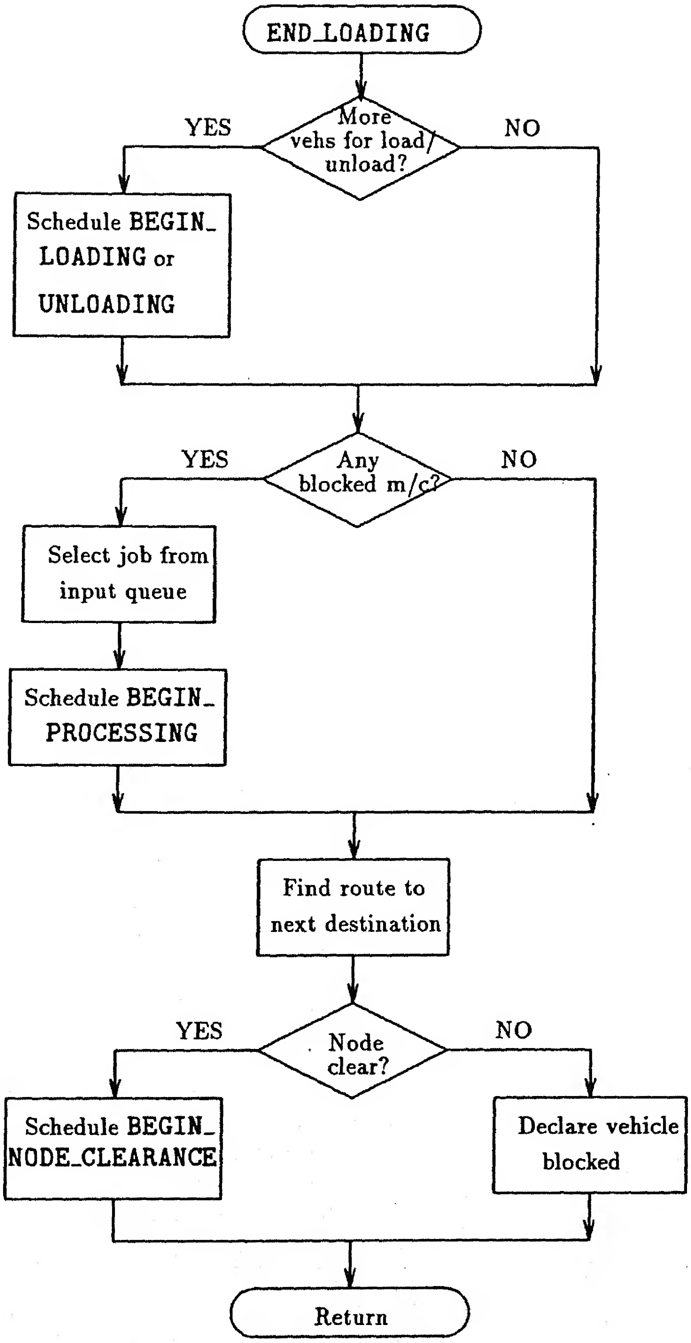

Figure 2.8: Flow chart for the event END_LOADING

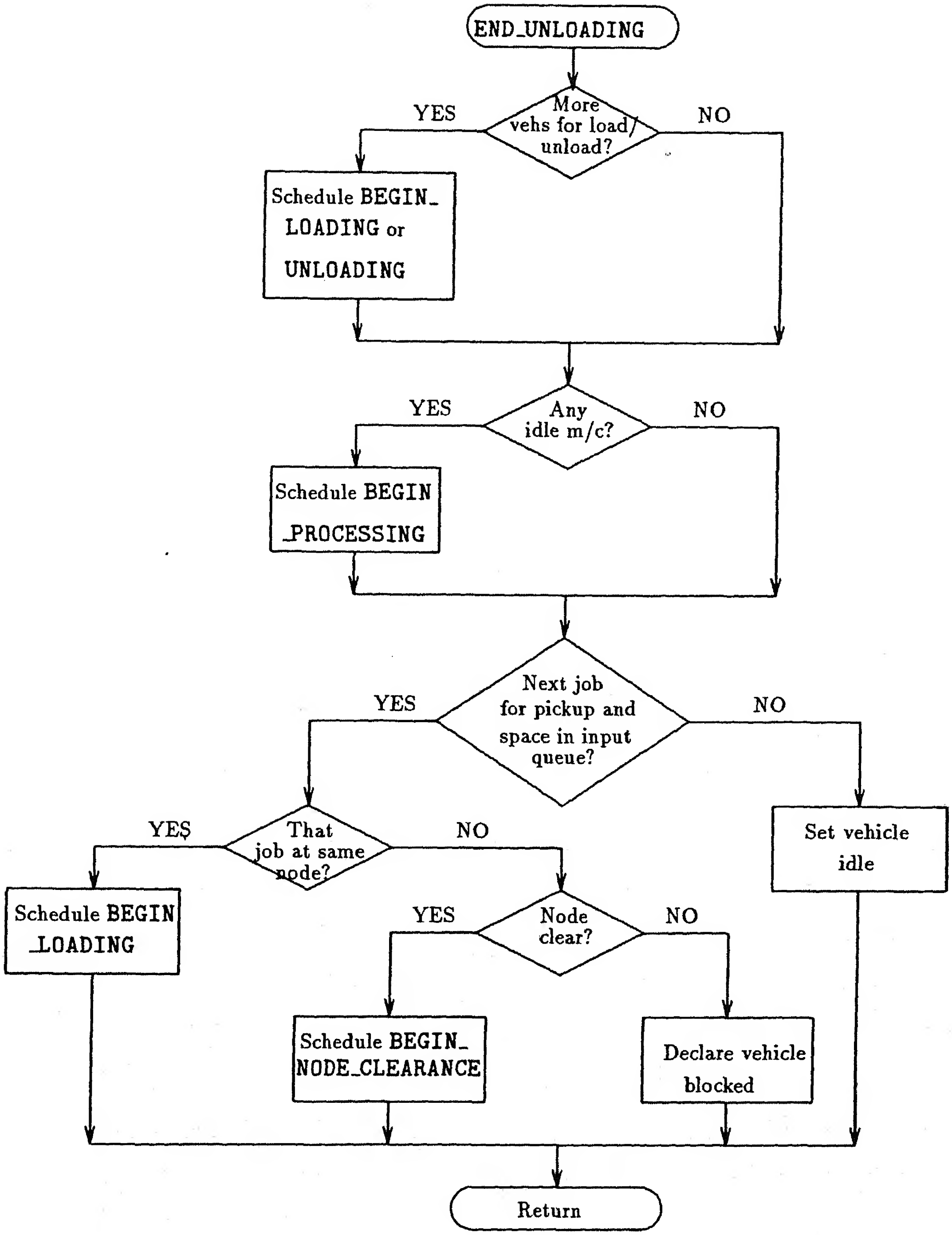

Figure 2.9: Flow chart for the event END_UNLOADING

Model verification and validation

Law and Kelton (1991) define these terms as follows. Verification is determining that a simulation computer programme performs as intended, that is, debugging the computer programme. Validation is concerned with determining whether the conceptual simulation model (as opposed to the computer programme) is an accurate representation of the system under study.

Following techniques of programme verification have been adopted for the designed simulator.

1. The programme has been written, run, and debugged in successive modules and subprogrammes.

2. The programme has been run under a variety of settings of the input parameters including job arrival rate, job type, job volume mix, process plans, process times, AGVS networks (different layouts, uni/bidirectionality of arcs), travelling times, loading/unloading times, buffer capacities, etc. For certain cases, some impossible conditions have been intentionally generated to give erroneous results, as expected. Hand calculations have been done for few conditions and the execution of the programme has been debugged against these calculations.

3. The programme has been debugged using "trace" mode of interactive debugger. This involves stopping the simulation at selected points in time and examining the contents of event list, state variables, certain statistical counters, etc. Various possible programme paths and extreme conditions (boundary points) have been generated and programme logic was debugged accordingly.

4. Sample means for simulation input job arrival and job type have been compared with the desired means to check if the values are being generated from the desired distributions.

The model has not been validated due to inaccessibility to an existing system. Due to the same reason, the representative input data have not been validated.

However, the input data used in the study do reflect the current technological trend, and similar values are being used by other researchers in other manufacturing scenarios encompassing different problem sets.

▪ *Variance reduction*

The variance reduction technique of using common random numbers is applied in the present work. The basic idea is to compare the alternative configurations under similar experimental conditions so that any observed differences in performance can be more confidently attributed to differences in the system configurations rather than to fluctuations of the experimental conditions. Separate streams of random numbers are dedicated to producing each particular type of input random variate, viz., job arrival and job type. The scheme ensures that each job arrives into the system at the same time and is assigned the same routeing and operation times for each setup considered.

▪ *Output data analysis*

System throughput rate is used as the main criterion of system performance in this study. Run length of simulation experiment is set for a time period of one shift (480 minutes). At the end of the shift, the system is reinitialized and simulation experiment is replicated. Five such replications constitute the output data for one system configuration alternative. The independence of replications is accomplished by using different random numbers for each replication. Allowing the first shift as a warm-up period within which transient behaviour of the system is exhibited, the results of the remaining four shifts (taken as sample size) are averaged for evaluating the system performance. The throughputs during these four shifts are independent and identically distributed random variables. The average so obtained is an unbiased point estimator for the system mean throughput rate, and an approximate 95% confidence interval for the mean can be calculated as

$$\bar{X}(4) \pm t_{3,0.975}\sqrt{\frac{S^2(4)}{4}},$$

where $\bar{X}(4)$ represents the average and $S^2(4)$ the variance of throughput in the four shifts* (Law and Kelton 1991). The 95% confidence intervals have been calculated for the average throughput rate for all the experimental settings in the present work, and it is observed that the individual shift results lie within the confidence intervals. The ratio of standard deviation of throughput rates of the four shifts to their average, $S(4)/\bar{X}(4)$, is observed to be less than 0.05 for all the experimental settings. The stochastic process in the simulation experiments is thus observed to stabilize.

*

and $t_{3,0.975}$ is the upper critical point for the t distribution with 3 degrees of freedom and 95% confidence interval

Chapter 3

Determination of AGV Fleet Size

3.1 Introduction

Determination of the number of vehicles required to provide for a specific manufacturing scenario a given level of material handling service is one of the fundamental decisions related to the design of an AGVS. The required number of vehicles is affected by several other decisions as well as certain dynamic operational behaviours of AGVS. These factors include the following.

1. the material flow intensity among the processing centres of the system,
2. the location of load transfer stations,
3. system flow path layout,
4. product routes,
5. vehicle attributes — speed, loading/unloading time, availability factor,
6. vehicle dispatching and routeing strategies, etc.

The individual impact of these decisions on AGVS design and their mutual interactions are difficult to estimate analytically.

The advantages of an AGVS are realized at a cost of an added capital expenditure incurred on acquisition of AGV fleet, layout of AGV guide path and related

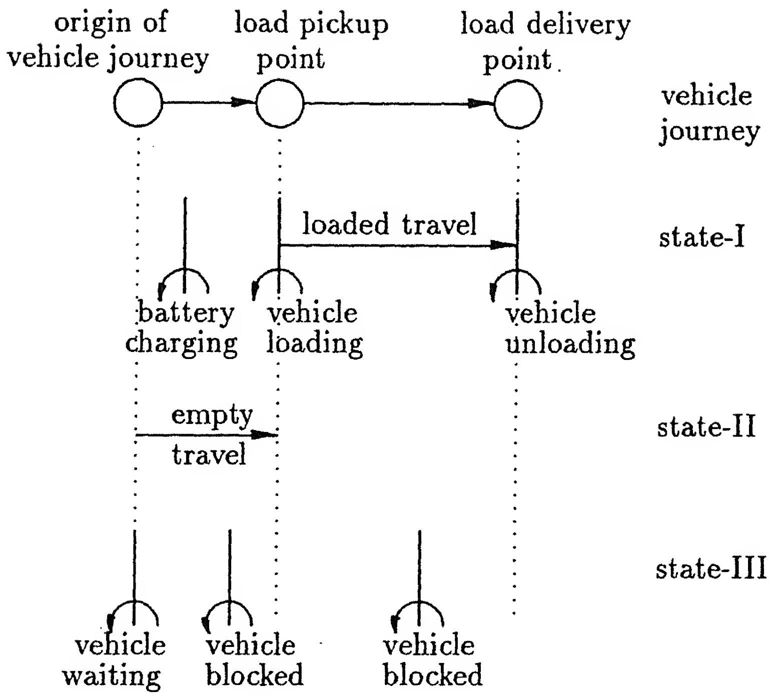

Figure 3.1: The states of an AGV in the system

hardware, and software for vehicle transport controllers. In order to minimize this capital outlay and also the subsequent operating costs, the first goal should be that of keeping the AGV fleet size at minimum which shall still be capable of meeting the throughput requirements imposed on the system. This would also result in a simple and manageable system.

A plan that achieves the objective of minimizing the AGV fleet size must begin by identifying how an AGV spends its time in the system. Figure 3.1 depicts different states and various activities in which an AGV is engaged while it is on the shop floor. A complete vehicle journey for the purpose of a load transportation task can be identified with three points of interest: (i) an origin of journey where the vehicle is located at the time of load transport assignment, (ii) a load P point where the vehicle is required to be loaded, and (iii) a load D point where the vehicle is unloaded. The last point becomes origin for the next journey. Further, the entire time span of the vehicle journey can accordingly be divided into the following three

mutually exclusive states.

State-I (Load handling): It refers to the activities of loading/unloading a unit load at a P/D station, transporting a unit load from a P station to a D station, and battery charging and other maintenance/repair works. The first two tasks are the ones for which AGVs are basically employed. The third aspect related to the vehicle availability factor, is an essential technical feature of an AGV that has to be considered.

State-II (Empty travel): It pertains to empty travel of a vehicle from origin of journey to a P station.

State-III (Waiting and blocking): It consists of a vehicle waiting idle at a D station for assignment of next material transportation task, and remaining in blocked state because of traffic congestion at any node in the network, whether it is travelling loaded or empty. Both these time components are wasteful because no productive work is done towards achieving material handling objectives.

This chapter discusses the major AGVS design issue of determining optimal AGV fleet size. A strategy for achieving this objective is highlighted first. An analytical method for computation of load handling time (state-I activities) is discussed and applied in deriving the basic minimum number of vehicles required in a manufacturing environment. Next, a new model is proposed to estimate the empty travel time of a vehicle (state-II activity) and the results are compared with those of some other models reported in the literature. State-III activities of a vehicle — idle waiting and blocked delay — are then discussed. All the discussed models are then compared for the illustrative example of Chapter 2. This is followed by a simulation study. The system performance is evaluated for different measures, and is compared with the results obtained from various analytical models.

3.2 Strategy for determination of AGV fleet size

Strategy for determination of an AGV fleet size in an FMS environment can be formulated as shown in Figure 3.2. The three states of an AGV as categorized in Figure 3.1 (load handling, empty travel, and waiting and blocking) are first identified. The time required for total number of loads to be moved (activities grouped under state-I) can be easily determined from the information available on material flow matrix and travel time matrix. Computation of the total time required for empty vehicle travel (the state-II activity) involves consideration of randomness in arrival pattern of load transport calls. It is not possible to determine accurately the empty vehicle travels because of this non-deterministic time phenomenon. Several approaches to estimate empty vehicle travel time have been advanced in the past. Approximation of vehicle waiting and blocking times (activities grouped under state-III) can be made using past empirical data obtained from other similar manufacturing system studies. The total time requirement is obtained by adding the time components of the three states and translated into the capacity, and then into the fleet size of the AGVS. The estimated value of the fleet size is not accurate enough owing to the dynamic behaviour of an AGVS which has not been captured by any analytical model so far. The operating dynamics of AGVS are associated with the randomness in load arrivals (type of load, inter-arrival time of loads), alternate process plans of a load, job and vehicle dispatching strategies, alternate vehicle routes, and vehicle traffic congestion status at intersection points. The stochastic behaviour of all these random factors point to simulation as the final approach to determine the required number of vehicles to be operated and controlled.

3.3 Determination of loaded travel time

The first step in sizing the number of vehicles required in an AGVS is typically the development of a design horizon (e.g., per shift) traffic requirement in the form of a from/to chart. Such a chart shows the number of loaded trips required "from" every load P station "to" every D station. This step entails surveying existing MHS demand patterns as well as defining future demand patterns. It also entails defining

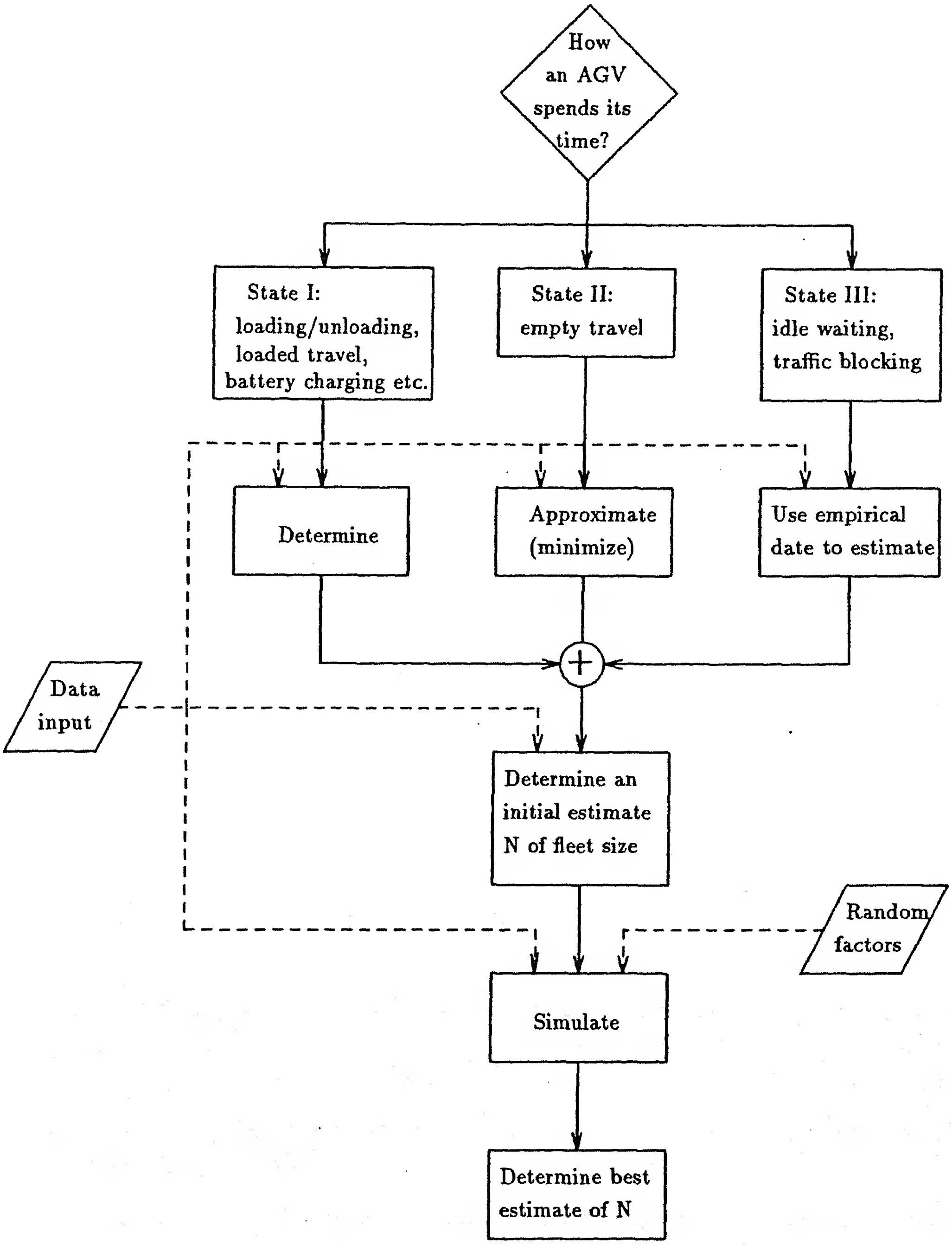

Figure 3.2: Strategy for determination of optimal AGV fleet size

a reasonable time horizon. The quantum of material flow within the system may be known or it can be computed from given job parameters. This study takes the latter approach. It considers an FMS environment where different part types, with known volume mix, are processed in known processing times at various centres using alternate process plans with known probabilities. Quantity of material flow in the system is computed from these job parameters as described below.

Notation

T = length of time period for which AGV activities are being planned,

C = number of processing centres in the system, excluding receiving/shipping centre(s),

m_k = number of machines in centre k,

n = number of P/D stations at all centres in the system,

t_{ij} = vehicle travelling time (loaded or empty) from the ith P/D point to the jth P/D point,

J = number of job types processed simultaneously,

v_i = volume mix of the ith job type,

S_i = number of different sequences in which job type i can be processed,

p_{ij} = probability that job type i is processed using sequence j,

f_{kl} = direct material flow from the kth centre to the lth centre due to a unit flow at the receiving/shipping centre,

pl_k = processing load on the kth centre due to a unit flow at the receiving/shipping centre,

pt_{ijk} = total processing time of job type i, using sequence j, at centre k. Thus, if job type i, using sequence j, visits centre k more than once, then pt_{ijk} denotes the sum of the processing times of all such individual visits,

μ_k = processing load per machine on the kth centre due to a unit flow at the receiving/shipping centre,

m_{ij} = number of unit loads to be moved from the ith centre to the jth centre,

NF_i = net material flow at the ith P/D point,

l_i = vehicle loading time at the ith P/D point,

u_i = vehicle unloading time at the ith P/D point,

η = availability factor of a vehicle,

T_l = total time required by vehicles for load transfer and transport,

T_e = total time required by vehicles for empty trips,

T_{wb} = total time for which vehicles remain idle and blocked,

T_a = total time a vehicle is available,

X_{ij} = number of empty trips vehicles make from the ith P/D point to the jth P/D point,

N = required number of vehicles.

Assuming that raw materials are received at and finished goods are shipped from the same receiving/shipping centre and denoting the receiving/shipping centre as the $(C+1)$th centre, the material flow from centre k to centre l, f_{kl}, due to a unit flow at the receiving/shipping centre is given by

$$f_{kl} = \sum_{i=1}^{J} v_i \sum_{j=1}^{S_i} p_{ij} \cdot \delta_{kl(ij)}, \; k, l = 1, 2, \ldots, C+1,$$

where $\delta_{kl(ij)}$ is the number of times job type i, using sequence j, visits centre l immediately after having been processed at centre k. Some properties of the flow matrix $\mathbf{F} \equiv (f_{kl})$ to satisfy the system flow characteristics are:

1. $f_{kk} = 0, k = 1, 2, \ldots, C+1$. This implies that there is no flow within the centres,

2. $\sum_{k=1}^{C} f_{C+1,k} = 1$. This ensures that jobs enter the system through receiving/shipping centre only,

3. $\sum_{k=1}^{C} f_{k,C+1} = 1$. This ensures that jobs leave the system through receiving/shipping centre only, and

4. $\sum_{l=1}^{C+1} f_{kl} = \sum_{l=1}^{C+1} f_{lk}$, $k = 1, 2, \ldots, C+1$. This indicates conservation of flow at all centres.

As a consequence of the fourth property of the flow matrix, consideration of assembly type of manufacturing environment is excluded from the analysis. Hence, material

flow balance at processing centres ensures that as many unit loads leave the centre as enter for processing needs. The structure and properties of the flow matrix discussed above were reported earlier by Mahadevan and Narendran (1990, 1993).

The processing load on centre k due to a unit flow at the receiving/shipping centre is given by

$$pl_k = \sum_{i=1}^{J} v_i \sum_{j=1}^{S_i} p_{ij} \cdot pt_{ijk}, \quad k = 1, 2, \ldots, C+1.$$

The processing load on a centre is shared by the number of machines present in the centre. All the machines operating in a centre are assumed to be identical in terms of their processing rate and availability factor. Thus, processing load per machine on centre k is given by

$$\mu_k = pl_k / m_k, \quad k = 1, 2, \ldots, C+1.$$

The vector $\vec{\mu}$ denotes the time spent by each machine of a centre in order to process one unit flow at the receiving/shipping centre. Let μ_K represent the maximum of all (μ_k), that is,

$$\mu_K = \max(\mu_k), \quad k = 1, 2, \ldots, C+1.$$

Then, the Kth processing centre becomes a bottleneck resource and thus limits and dictates the production throughput of the system. If T is the length of the time period for which the AGV activities are being planned, then T/μ_K is the maximum number of unit loads that can be produced by the Kth centre, and consequently by the system. The total number of unit loads to be moved from centre k to centre l, m_{kl}, is obtained by multiplying the flow f_{kl} by this quantity. Thus,

$$m_{kl} = (T/\mu_K) \cdot f_{kl}, \quad k, l = 1, 2, \ldots, C+1.$$

As a consequence of the assumptions and analysis of the above discussed model, the centres having $\mu_k < \mu_K$ will have certain amount of unutilized capacity. Thus, the analysis also points towards the task of balancing workload among the processing centres. The method and equation for computing the material flow matrix from the given job parameters, as discussed above, constitute the basic analytical result of the AGVS modelling effort in this study.

Let the total number of load transfer stations at all centres in the system be denoted by n. Such P/D stations of a centre may be co-located or situated at different sites. Thus, n is numerically either greater than or equal to the number of centres in the system, $C+1$. It is assumed that both the activities of loading and unloading at the ith point are performed in constant times, l_i and u_i , respectively. Besides the P/D stations, the guide path network of the system also consists of a number of intersection points. A static vehicle routeing strategy has been adopted in this analysis, wherein a vehicle always follows a predetermined route from one point to another and takes t_{ij} amount of time while travelling from the ith point to the jth point. All the vehicles operating on the shop floor are considered to be unit load carrier type, identical in terms of their load carrying capacity, travelling speed (whether loaded or empty), and availability factor η.

Since an AGV transports one unit load at a time, therefore, the number of loaded trips to be executed by the fleet will equal the number of unit loads to be moved in the system during the planning horizon, T. Let the required number of vehicles be represented by N. Denoting the total time the fleet will be engaged in the activities of load transfer and transport by T_l , and the total time a vehicle will be effectively available by T_a , following computations can be made.

$$\begin{aligned} T_l &= \sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij} \cdot (l_i + t_{ij} + u_j) , \\ T_a &= \eta \cdot T , \\ N_{\min} &= \left\lceil \frac{T_l}{T_a} \right\rceil^{+} , \end{aligned}$$

where $\lceil x \rceil^{+}$ denotes the smallest integer greater than or equal to x. Thus, at least $N_{\min}$ AGVs will be required in the system.

Muller (1983) presented a similar formula to determine the AGV fleet size:

$$N = \sum_{i=1}^{n} c_i \cdot f_i / T_a ,$$

where c_i is the cycle time and f_i the frequency of transport operations for the ith P/D station.

3.3.1 Illustrative example

The minimum AGV requirement for the system described in the previous chapter (Figure 2.4 and Tables 2.1 – 2.3) is computed through the above outlined steps as follows.

1. The flow matrix $\mathbf{F}$ is first computed. For example,

$$\begin{aligned} f_{46} &= 0.2\,[\,0.125\,(4 \times 1 + 4 \times 0)] \; + \\ &\quad\; 0.3\,[\,0.25\,(2 \times 1 + 2 \times 0)] \; + \\ &\quad\; 0.5\,[\,0.5\,(2 \times 0)] \\ &= 0.25 \text{ unit loads.} \end{aligned}$$

   The complete flow matrix is shown in Table 3.1. It is observed that $\mathbf{F}$ satisfies the properties discussed previously.

2. Processing loads on the centres and processing load per machine for each centre are then computed. For example,

$$\begin{aligned} pl_3 &= 0.2\,[\,0.125\,(4 \times 12 + 2 \times (12 + 12) + 2 \times 0)] \; + \\ &\quad\; 0.3\,[\,0.25\,(2 \times 17 + 2 \times 0)] \; + \\ &\quad\; 0.5\,[\,0.5\,(1 \times 18 + 1 \times 0)] \\ &= 9.45 \text{ min, and} \\ \mu_3 &= 9.45/4 = 2.3625 \text{ min.} \end{aligned}$$

   Table 3.2 gives the results of the processing load computations.

3. The maximum of all μ_ks is found to be 2.4 min for centre 6. Hence, the shop production level is constrained by this centre. For a planning period of 480 minutes, the maximum achievable shop throughput is (480/2.4), which is equal to 200 unit loads.

4. The inter-centre material movement matrix (m_{ij}) is then computed by multiplying the flow matrix of Table 3.1 by 200. Table 3.3 shows the number of unit loads to be moved among the various centres for maximum shop throughput target.

Table 3.1: Flow matrix

		To centre						
		1	2	3	4	5	6	
	1	–	0.50	0.10	0.40	0.00	0.00	1.00
	2	0.10	–	0.00	0.00	0.25	0.25	0.60
From	3	0.50	0.00	–	0.00	0.00	0.10	0.60
centre	4	0.00	0.00	0.25	–	0.00	0.25	0.50
	5	0.40	0.00	0.00	0.00	–	0.10	0.50
	6	0.00	0.10	0.25	0.10	0.25	–	0.70
		1.00	0.60	0.60	0.50	0.50	0.70	3.90

Table 3.2: Processing loads (min)

Centre	Processing load, pl_k	Processing load per machine, μ_k
1	0.00	0.0000
2	9.45	2.3625
3	9.45	2.3625
4	8.55	2.1375
5	8.55	2.1375
6	12.00	2.4000

Table 3.3: Material flow matrix (unit loads per shift)

		To centre						
		1	2	3	4	5	6	
	1	–	100	20	80	0	0	200
	2	20	–	0	0	50	50	120
From	3	100	0	–	0	0	20	120
centre	4	0	0	50	–	0	50	100
	5	80	0	0	0	–	20	100
	6	0	20	50	20	50	–	140
		200	120	120	100	100	140	780

5. From the m_{ij} values of Table 3.3 and the vehicle travel time data of Table 2.3, the following computations are made.

$$\begin{aligned} T_l &= 3090 \text{ min}, \\ T_a &= 480 \text{ min per vehicle, and} \\ N_{\min} &= \lceil 3090/480 \rceil^{+} = 7 \text{ vehicles.} \end{aligned}$$

3.4 Estimation of empty vehicle travel time

A vehicle after delivering its load at a D station becomes empty and ready for assignment of next load transportation task. It may be assigned the task starting from the same point if the load transfer station is a co-located P/D point and there is a load awaiting pickup from there, or any other P station may demand services of the vehicle. Even if the centre's P/D stations are co-located, the vehicle may have to travel empty because it is not necessary that the vehicle will always find a load waiting to be picked up from the same point where it has just delivered its load. The call to pick up a load may come, in real time, from some other P station. Moreover, if the P/D stations of the centre are situated at different locations, then vehicle has necessarily to travel empty to a P station for its next load transportation task. Thus, loaded travels of the vehicle would be interspersed with empty travels.

The dynamic behaviour of AGVS makes it difficult to predict actual amount of empty vehicle travels. Movement of empty vehicles is highly dependent on short term operational decisions like scheduling of individual jobs and vehicle dispatching rules. The only way an AGVS designer can circumvent this difficulty is by coming up with some estimate of empty vehicle trips. The attempt should be directed towards minimizing this time component, though the actual amount of time spent by the fleet in making the empty travels may be higher than what is approximated.

Let NF_i denote the net material flow at the ith P/D point. It is defined as the difference between the total number of unit loads delivered at the ith point and the total number of unit loads picked up from the point. In case the P/D stations of a

centre are co-located, the net flow at that point would be zero. Thus, in general,

$$NF_i = \sum_{j=1}^{n} m_{ji} - \sum_{j=1}^{n} m_{ij}.$$

Since it is assumed that the total net material flow is conserved in the system, therefore, the sum of all the net flows at all the points will be zero, that is, $\sum_{i=1}^{n} NF_i = 0$.

Let X_{ij} denote the number of empty trips the fleet makes from the ith point to the jth point, and T_e the total time required to make all such trips. Thus,

$$T_e = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot X_{ij}.$$

The next subsection provides a brief summary of the previous work reported in the literature related to estimation of the value of T_e.

3.4.1 Literature review

Maxwell (1981), and Maxwell and Muckstadt (1982) did pioneering work in analytical modelling of operational features of an AGVS. In an environment comprising primarily of assembly operations for finished products, they proposed a time-independent model to estimate the minimum number of vehicles required to support the material transportation needs. The empty vehicle travel time was estimated by computing the net flows, NF_i, at each P/D station which represented number of empty trips into or out of that station. The stations with positive net flows had empty trips available to be assigned to other stations with negative net flows. A standard transportation problem was formulated which assigned empty vehicle trips between various stations minimizing the total empty vehicle travel time. The resulting problem

$$\begin{aligned}
\text{Minimize} \quad & \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot X_{ij}, \\
\text{subject to} \quad & \sum_{j=1}^{n} X_{ij} = NF_i \text{ if } NF_i \geq 0, \quad \forall i, \\
& \sum_{j=1}^{n} X_{ji} = |NF_i| \text{ if } NF_i \leq 0, \quad \forall i, \\
& \text{each } X_{ij} \text{ is a non-negative integer}
\end{aligned}$$

was solved to obtain optimal values of empty vehicle trips. Finally,

$$(T_e)_{\text{Maxwell}} = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot (X_{ij})_{\text{Maxwell}}.$$

The work of Maxwell and Muckstadt (1982) was extended by Leung *et al* (1987), who additionally considered vehicle types of different load carrying capacity and speed. Lin (1990) wrote a computer programme to determine minimum number of vehicles required in an AGVS, based on Maxwell's model. However, rather than applying the linear programming approach directly, his solution methodology translated the problem into a minimum cost flow problem and then used an out-of-kilter algorithm.

Beisteiner and Moldaschi (1983) proposed two thumb-rules for estimating empty vehicle travel time. In the first case, they approximated total empty vehicle travel time to be equal to the product of total number of empty trips, X_t, as given by total net flows (either all positive or all negative), and average loaded vehicle trip time, $\bar{t}$. The underlying assumption was that every empty trip consumed as much time as an average loaded trip. Thus,

$$\begin{aligned}
\bar{t} &= \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot m_{ij} \Big/ \sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}, \\
X_t &= \sum_{i=1}^{n} NF_i, \ \ \forall NF_i > 0 \\
&= \sum_{i=1}^{n} |NF_i|, \ \ \forall NF_i < 0, \\
(T_e)_{\text{Beisteiner-I}} &= \bar{t} \cdot X_t.
\end{aligned}$$

In the second case, they approximated total empty vehicle travel time to be equal to total loaded vehicle travel time. Thus,

$$(T_e)_{\text{Beisteiner-II}} = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot m_{ij}.$$

Kuhn (1983) presented a more realistic estimation method of determining empty vehicle travels. Rather than the net flows he considered total number of loads delivered at a station as the number of empty vehicle trips starting from that station.

These empty vehicle trips were then routed to various other stations in proportion to the total number of load pickups from those stations. Thus,

$$
\begin{aligned}
(X_{ij})_{\text{Kuhn}} &= \begin{pmatrix}\text{number of loads}\\ \text{delivered at } i\end{pmatrix} \cdot \begin{pmatrix}\text{fraction of total loads}\\ \text{picked up from } j\end{pmatrix} \\
&= \left(\sum_{k=1}^{n} m_{ki}\right) \cdot \left(\sum_{k=1}^{n} m_{jk} \Big/ \sum_{k=1}^{n}\sum_{l=1}^{n} m_{kl}\right), \\
(T_e)_{\text{Kuhn}} &= \sum_{i=1}^{n}\sum_{j=1}^{n} t_{ij} \cdot (X_{ij})_{\text{Kuhn}}.
\end{aligned}
$$

Kuhn's model has been widely used by other researchers (Yim and Linn 1993).

Malmborg (1990) suggested a scheme for computing empty vehicle travel time which is somewhat at variance with the approach proposed by Maxwell. Important differences arise on both the counts — number of empty trips and travel time of each such trip. The frequency of empty trips was based on total number of loads delivered at or picked up from each station rather than the net flows. Further, instead of minimizing empty travel time Malmborg's scheme maximized it. It meant that each vehicle, after having unloaded its load at a delivery station and become empty, was routed to the farthest away station. Thus,

$$
\begin{aligned}
\text{Maximize} \quad & \sum_{i=1}^{n}\sum_{j=1}^{n} t_{ij} \cdot X_{ij}, \\
\text{subject to} \quad & \sum_{j=1}^{n} X_{ij} = \sum_{j=1}^{n} m_{ji}, \quad \forall i, \\
& \sum_{j=1}^{n} X_{ji} = \sum_{j=1}^{n} m_{ij}, \quad \forall i, \\
& \text{each } X_{ij} \text{ is a non-negative integer.}
\end{aligned}
$$

The total empty vehicle travel time thus obtained was considered by Malmborg as an upper bound solution as opposed to the lower bound one of Maxwell's model. Further, he argued that actual empty travel would be a weighted average of these two bounds. The weighing factor would be a function of vehicle dispatching strategies in operation, and a management defined constant. Thus,

$$
(T_e)_{\text{Malmborg}} = \sum_{i=1}^{n}\sum_{j=1}^{n} t_{ij} \cdot (X_{ij})_{\text{Malmborg}}.
$$

Sinriech and Tanchoco (1992a) developed a multi-criteria optimization model considering cost and throughput to determine the AGV fleet size. They used trade-off ratio between the two goals and introduced management decision tables to enhance the solution procedure.

3.4.2 Proposed model

An approximation methodology is developed here to estimate the total empty vehicle travel time. The model begins with the objective of minimizing empty vehicle trips. The frequency of such trips from/to a station is constrained by total number of loads delivered at/picked up from that station. Consequently, this number is numerically greater than or equal to the net flows as considered by Maxwell. This is done in order to make the bound on empty trips more realistic. If a processing centre has co-located P/D stations and material flow is conserved there, then according to Maxwell's model, number of empty trips starting from or ending at that station is zero. The result is an under-estimation of actual number of empty trips. This follows from the fact that every loaded vehicle after delivering its load may not find another load ready to be picked up from the same station. The call to pick up a waiting load may come from some other P station. In other words, some empty vehicle trips will be mandatory. Thus, in the proposed model, as many empty trips originate from a station as loaded trips end there, and as many empty trips terminate at the station as loaded trips start from there. In other words, "supplies" of vehicles are available at D stations in the quantity in which loaded trips end up at these D stations, and vehicles are "demanded" at P stations in the quantity in which loaded trips start from these P stations. However, there may be some loaded trips ending at a point which again start as loaded trips, as it happens when a vehicle after delivering its load does find another load ready to be picked up from the same point. An upper bound on such trips starting from a station is put in proportion to the total number of loads picked up from the same station. The model is presented below.

$$\begin{aligned}
\text{Minimize} \quad & \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot X_{ij}, \\
\text{subject to} \quad & \sum_{j=1}^{n} X_{ij} = \sum_{j=1}^{n} m_{ji}, \quad \forall i, \\
& \sum_{j=1}^{n} X_{ji} = \sum_{j=1}^{n} m_{ij}, \quad \forall i, \\
& X_{ii} \leq \left[\left(\sum_{j=1}^{n} m_{ji} \right) \cdot \left(\sum_{j=1}^{n} m_{ij} \Big/ \sum_{k=1}^{n} \sum_{l=1}^{n} m_{kl} \right) \right]^{+}, \\
& \text{each } X_{ij} \text{ is a non-negative integer.}
\end{aligned}$$

The third constraint in the above model represents maximum number of vehicle trips which should have started as empty from a point, but instead start as loaded from the same point. Hence, at most X_{ii} loaded trips ending at the ith station will again start as loaded trips from the same station. Thus,

$$(T_e)_{\text{Proposed}} = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot (X_{ij})_{\text{Proposed}}.$$

It is to be noted that in an FMS layout where all the processing centres have different sites for load pickup and delivery (i.e., net flows are non-zero at all stations), the results obtained from the proposed model would coincide with that of Maxwell.

An initial estimate of the required fleet size, N, can be obtained from the value of T_e which is computed using any of the above discussed models (or any other preferred technique).

3.5 Vehicle waiting and blocking time

Vehicle waiting time (idle wait) refers to the time an AGV spends while waiting empty at a D station for assignment of the next load transportation task. Vehicle blocking time (blocked delay) is the time an AGV remains in a blocked state because of traffic congestion at any node in the guide path network, while it is travelling either loaded or empty. Both these time components should be minimized, if not eliminated completely. The dynamic behaviour of AGVS may necessitate these time components to be present and also render them incalculable in advance. They

cannot be computed *a priori* because they are dependent upon the AGV fleet size, a parameter which the designer wishes to determine in the first place. The more is the number of vehicles operating on the shop floor at a time, the more is the likelihood of their getting blocked as well as waiting for transport calls. Mutual interference among vehicles reduces the potential availability of a vehicle. Other factors on which vehicle waiting and blocking times depend are vehicle dispatching and routeing strategies, guide path layout, and vehicle clearance procedures at intersections. Vehicle blocking phenomenon is manifested more frequently in an AGVS consisting of bidirectional arcs.

Inter-dependency of multiple decision variables makes modelling task of vehicle waiting and blocking phenomena a difficult one. Not much research work has been carried out in this direction. A few of the empirical and analytical approaches for approximation of these time components which have been reported in the literature are summarized below.

3.5.1 Literature review

Koff (1985) presented empirical approximation of vehicle idleness and blocking time factors in the process of determination of the fleet size. These factors are facility dependent and the range of values suggested for them is as follows.

$$\begin{aligned} \alpha_1 &= \text{vehicle idleness factor} \\ &= \text{10 to 15\% of total loaded vehicle travel time,} \\ \alpha_2 &= \text{vehicle blocking factor} \\ &= \text{10 to 15\% of total loaded vehicle travel time.} \end{aligned}$$

Vehicle idleness factor includes both the empty travel and idle wait of a vehicle. Let T_{wb} represent the total time the fleet has to wait idle and remain blocked. Then,

$$(T_e + T_{wb})_{\text{Koff}} = (\alpha_1 + \alpha_2) \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} \cdot m_{ij}.$$

Kulweic (1982, 1984) had earlier presented a similar empirical formula:

$$T_l + (T_e + T_{wb})_{\text{Kulweic}} = \frac{T_l}{(1-\alpha_1)(1-\alpha_2)},$$

$$\text{or } (T_e + T_{wb})_{\text{Kulweic}} = \left(\frac{\alpha_1 - \alpha_1\alpha_2 + \alpha_2}{(1-\alpha_1)(1-\alpha_2)}\right) \cdot T_l,$$

where α_1 = vehicle emptiness and idleness factor, $0.2 \le \alpha_1 \le 0.4$,

and α_2 = vehicle blocking factor, $\alpha_2 = 0.15$.

In other words,

$$0.5T_l \le (T_e + T_{wb})_{\text{Kulweic}} \le T_l.$$

A control zone modelling of a bidirectional AGVS by Malmborg (1990) presented estimates of vehicle blocking times in various control zones by applying Markov chains and transition probabilities. He assumed that each control zone is occupied by only one vehicle at a time and that that vehicle has travelled half of the control zone distance when other vehicles arriving at the control zone are blocked. The assumption of only one vehicle occupying an arc at a time is not realistic for an FMS layout consisting of long stretches of guide path arcs since this would result in under-utilization of the guide path.

No approximation method for determining idle waiting and blocking times of a vehicle is developed in this work. Once the values of T_e and T_{wb} have been estimated by any of the discussed models, the fleet size can be calculated as follows.

$$N = \left\lceil \frac{T_l + T_e + T_{wb}}{T_a} \right\rceil^+ .$$

3.6 Illustrative example

The FMS facility illustrated in Chapter 2 (Figure 2.4) is considered here for illustration purpose. Results obtained after applying the analysis of various models discussed in the previous two sections are summarized in Table 3.4. The analysis of the results is taken up in the next subsection. The formulated mixed integer linear programme for estimation of empty travel time by the proposed model is presented in Appendix B.

Table 3.4: Estimation of AGV fleet size by various analytical models

Model	Estimated empty and idle/blocked times[a], $T_e + T_{wb}$ (min)	Estimated fleet size, N
Minimum	0	7
Maxwell	0	7
Beisteiner-I	0	7
Beisteiner-II	2310	12
Kuhn	2370	12
Koff[b]	578	8
Kulweic[c]	2101	11
Malmborg	3510	14
Proposed	1333	10

[a]idle and blocked times estimated by Koff's and Kulweic's models only.
[b]$\alpha_1 + \alpha_2 = 0.25$ for this model.
[c]$\alpha_1 = 0.3$ and $\alpha_2 = 0.15$ for this model.

Table 3.5: Estimation of AGV fleet size under different shop loading levels

Model	Estimated AGV fleet size under loading factor (unit loads per shift)					$\frac{(T_e + T_{wb})^a}{T_l}$
	40	80	120	160	200	
Minimum	2	3	4	6	7	0
Maxwell	2	3	4	6	7	0
Beisteiner-I	2	3	4	6	7	0
Beisteiner-II	3	5	7	9	12	0.75
Kuhn	3	5	7	10	12	0.77
Koff	2	4	5	7	8	0.19
Kulweic	3	5	7	9	12	0.68
Malmborg	3	6	9	11	14	1.14
Proposed	2	4	6	8	10	0.43

[a]T_{wb} for Koff's and Kulweic's models only

3.6.1 Load sensitivity analysis

The results presented in the Table 3.4 are specific for a shop loading factor of 200 unit loads per shift. In order to observe the behaviour of the results with respect to load variations, load levels are allowed to decrease to 40, 80, 120, and 160 unit loads per shift. The results have been tabulated in Table 3.5.

The last column of Table 3.5 expresses total empty travel time plus waiting and blocking time, as a fraction of total load transfer and transport time. This fraction is a constant quantity for each model since the numerator increases in direct proportion to the denominator as loading factor is increased from 40 unit loads to 200 unit loads per shift. Different values of this fraction for different models are indicators to the optimizing effect of each model.

The results of Table 3.5 have been plotted in Figure 3.3. The figure shows variation of the estimated fleet size with respect to the shop loading levels for different models. The increasing pattern of each model indicates the necessity of a larger fleet size as the total number of loads to be moved within the system is increased. The models presented by Maxwell, Beisteiner-I, and Koff give comparatively low values of the estimated number of vehicles to be employed at different load levels. In fact, the results of the first two of these three models coincide between themselves and with the minimum AGV requirement calculation of Section 3.3 for the entire range of load levels. This behaviour of the two models is attributed to the fact that all the centres have co-located P/D stations and total material flow is conserved in the system, resulting in zero net flows at each point. Simulation studies (Egbelu 1987a, Malmborg 1990) have shown that the three models consistently under-estimate the empty vehicle travel time, thereby resulting in low values of the fleet size. On the other hand, Malmborg's model results in over-estimation of the fleet size since it estimates relatively higher value of empty vehicle travel time. The models suggested by Kuhn, Beisteiner- II, Kulweic, and the proposed model present a somewhat more realistic picture of the situation when compared with the rest of the models. The estimate of the AGV fleet size obtained from the proposed model is a logical weighted average between the upper bound solution of Malmborg's model and lower bound solution given by Maxwell's model. This estimate is a weighted statistic

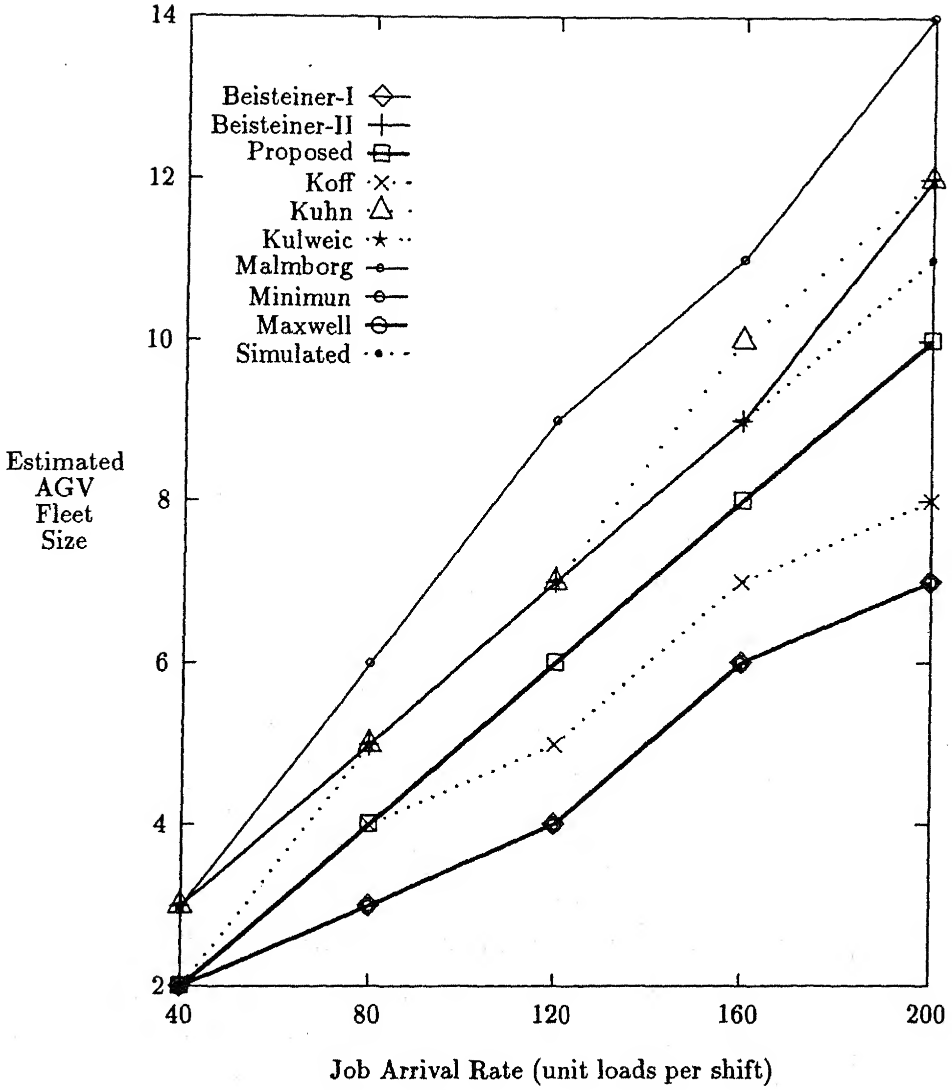

Figure 3.3: Estimation of AGV fleet size by various models

because it awards each P/D station its due weight of total number of loads picked up from/delivered at there. And the methodology is an optimizing one because it aims to minimize empty travel time by assigning these empty trips between pairs of stations in an optimal way. The figure also shows the result of the simulation study which has been discussed in Section 3.7.

3.6.2 Criticality of material handling resource

The ratio of mean processing time of a unit load to mean handling (transfer and transport) time of a unit load, denoted here as P/H ratio, is an index that represents the criticality of the transport resource in a manufacturing system. The criticality of a resource can be defined as a measure which is positively correlated to the probability that the resource becomes a bottleneck resource in the system (Kim and Tanchoco 1993b). Other critical ratios of similar nature that have been discussed by other researchers include cycle ratio (Tanchoco *et al* 1987), T/P ratio (Han and McGinnis 1989), P/T ratio (Kim and Tanchoco 1993b), etc. In this study, P/H ratio is used to measure the criticality of the transport system. Using the earlier defined notation, the components of P/H ratio are defined as follows.

$$
\begin{aligned}
P &= \text{mean processing time of a unit load} \\
&= \sum_{i=1}^{J} v_i \sum_{j=1}^{S_i} p_{ij} \cdot \begin{pmatrix}\text{total processing time at all centres} \\ \text{in } j\text{th sequence of } i\text{th job type}\end{pmatrix}, \\
H &= \text{mean handling time of a unit load} \\
&= \sum_{i=1}^{J} v_i \sum_{j=1}^{S_i} p_{ij} \cdot \begin{pmatrix}\text{total load transfer and} \\ \text{transport time in } j\text{th se-} \\ \text{quence of } i\text{th job type}\end{pmatrix} \\
&= T_l \Big/ \sum_{i=1}^{P} \sum_{j=1}^{S_i} m_{ij} \, .
\end{aligned}
$$

For the example of Section 3.3, at a loading factor of 200 unit loads per shift, the ratio is computed as: P/H ratio = 48/15.45 = 3.107. This value of P/H ratio implies that a unit load spends nearly three-fourths of its theoretical flow time in the system under processing and one-fourth in handling activities. The processing

Table 3.6: Variation of AGV fleet size with P/H ratio

Model	Estimated AGV fleet size under P/H ratio 3.107	1.553	1.036
Minimum	7	13	20
Maxwell	7	13	20
Beisteiner-I	7	13	20
Beisteiner-II	12	23	34
Kuhn	12	23	35
Koff	8	16	23
Kulweic	12	22	33
Malmborg	14	28	42
Proposed	10	19	28

resource is three times more critical than the material handling resource, or, in other words, their relative criticalities are in the ratio of 75:25 approximately.

To see the effect of the P/H ratio on the AGV fleet size, two more values of P/H ratio are used, viz., 60:40 (P/H = 1.553) and 50:50 (P/H = 1.036). Table 3.6 shows the variation of estimated fleet size with respect to P/H ratio, for various models discussed in the previous two sections.

Figure 3.4 is a graphical representation of the above tabulated results. It shows that Malmborg's model relatively over-estimates empty travel time resulting in determination of higher fleet size. On the other hand, under-estimation of empty travel time (Maxwell, Beisteiner-I, Koff) leads to lower fleet sizes. The models presented by Beisteiner-I, Kuhn, Kulweic, and the proposed model occupy a somewhat central location between the two extreme bounds of Malmborg's model and the minimum AGV requirement. The figure also shows results of the simulation study which has been discussed in Section 3.7.

3.7 Simulation study

In an FMS where process order generation is random, and the physical location of these generated orders does not follow any recognized pattern, the only reliable

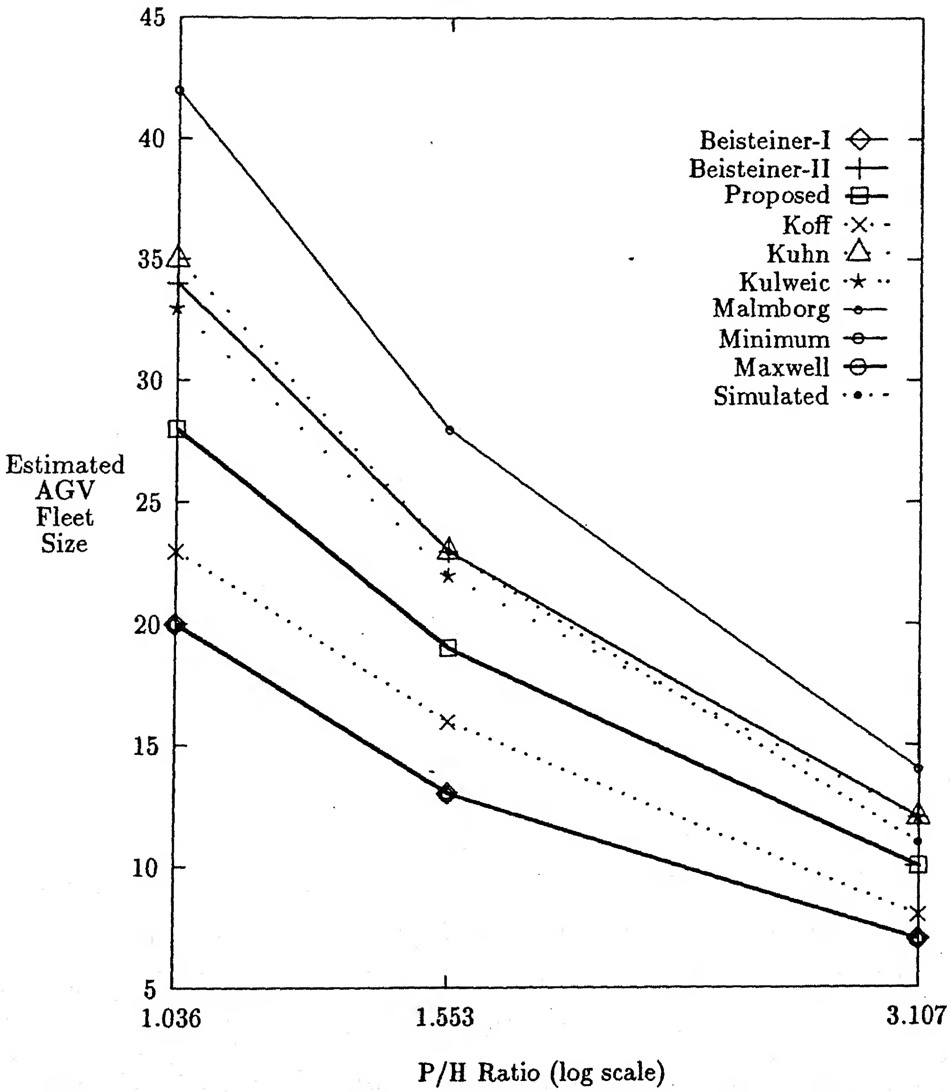

Figure 3.4: Variation of estimated fleet size with P/H ratio

method for estimating vehicle requirement is through a detailed simulation. Dynamic behaviour of the system cannot be captured in the decision making process involving only mathematical techniques. Several authors (Ashayeri *et al* 1985, Newton 1985, Egbelu 1987a, 1987b, Cheng 1987, Ozden 1988, Jaikumar and Solomon 1990, Lee *et al* 1990, Gobal and Kaslingam 1991) have used simulation methodology for determination of the AGV fleet size encompassing various problem scenarios. Tanchoco *et al* (1987a) used queueing theory based CAN-Q (Computerized Analysis of Network of Queues) model to make an initial estimate of fleet size prior to a follow-up simulation study. Wysk *et al* (1987) used a preprocessor to CAN-Q for the above study.

In order to investigate the effectiveness of the various models to estimate AGV requirement, as discussed in Sections 3.4 and 3.5, a simulation analysis of the hypothetical FMS is undertaken. The aim of the exercise is to determine an optimal AGV fleet size which maximizes shop throughput rate of the illustrative FMS.

Tables 2.1, 2.2 and 2.3 describe the input data for the programme. Each processing centre has a unique input queue of parts waiting to be processed, and an output queue of processed parts. With the exception of input/output queues of the receiving/shipping centre, all other queues are assumed as capacitated. The effect of the buffer capacity on the system operational behaviour has been further analyzed in Chapter 5. Parts arrive into the system at a Poisson arrival rate with a mean of 200 jobs per shift. Processing of parts at any centre is performed on FCFS basis. Different process plans for a specific part type are followed with specified probabilities. Static routeing strategy is adopted wherein a vehicle follows the minimum distance path between any two given locations. Vehicles cross a check zone sequentially on FCFS basis. For a job demanding transport service, the nearest idle vehicle (NV) is assigned the task. On the other hand, if there are more than two jobs vying for the service of an idle vehicle, then the vehicle is assigned to pickup that job which arrived earliest into the system (EJAT).

The manufacturing scenario discussed above is simulated for a period of five shifts resulting in five replications of length one shift each. Analytical modelling of AGVS, as discussed in previous sections, is used to help in making initial decision

Table 3.7: Throughput and other results of simulation experiment

No. of AGVs	Shift	Throughput	Vehicle activity time (%) Load handling	Empty travel	Idle	Blocked	Vehicle dispatching ratio
8	I	128	54.39	39.42	4.86	1.22	0.11
	II	132	55.54	43.13	0	1.36	0
	III	133	55.08	43.43	0	1.48	0
	IV	138	55.80	42.86	0	1.34	0
	V	137	55.28	43.28	0	1.43	0
		135	55.43	43.18	0	1.40	0
9	I	140	53.15	37.75	7.50	1.51	0.20
	II	151	55.84	42.66	0	1.50	0
	III	149	55.51	42.96	0	1.54	0
	IV	161	55.61	42.73	0	1.66	0
	V	155	57.06	41.23	0	1.72	0
		154	56.01	42.40	0	1.61	0
10	I	148	51.78	35.16	11.27	1.74	0.43
	II	162	54.62	43.51	0	1.85	0
	III	174	55.56	42.21	0	2.21	0
	IV	177	56.22	41.77	0	2.01	0
	V	171	55.75	42.39	0	1.74	0
		171	55.54	42.47	0	1.95	0
11	I	153	48.62	26.31	23.26	1.71	1.78
	II	177	54.39	41.91	1.57	2.12	0.04
	III	189	55.33	41.94	0.50	2.22	0.02
	IV	191	55.60	42.27	0.15	2.00	0.01
	V	188	55.16	42.25	0.47	2.13	0.03
		186.25	55.12	42.09	0.67	2.12	0.03

contd.

No. of AGVs	Shift	Throughput	Vehicle activity time (%) Load handling	Empty travel	Idle	Blocked	Vehicle dispatching ratio
12	I	156	45.34	15.11	37.22	1.75	4.88
	II	170	50.16	31.34	17.23	1.73	0.64
	III	194	50.07	35.14	12.70	2.11	0.33
	IV	195	51.23	35.00	11.35	1.93	0.41
	V	188	50.94	35.14	12.15	1.80	0.33
		186.75	50.73	34.16	13.36	1.89	0.43
13	I	155	41.66	15.17	40.95	1.66	5.25
	II	174	46.27	27.72	24.40	2.04	0.92
	III	189	46.57	25.95	25.65	1.87	0.82
	IV	198	50.05	31.03	16.82	2.02	0.75
	V	203	48.94	29.37	19.32	2.00	0.72
		191	47.96	28.52	21.55	1.98	0.80
14	I	158	38.83	11.18	47.88	1.54	6.69
	II	179	44.05	21.92	32.83	1.70	1.08
	III	189	43.61	24.82	29.64	1.74	0.89
	IV	197	45.28	22.13	31.14	1.64	1.22
	V	198	45.43	25.76	26.70	1.90	0.89
		190.75	44.60	23.66	30.08	1.75	1.02

related to determination of an optimal AGV fleet size. Accordingly, as predicted by various models, the AGV fleet size is varied from 8 to 14. Results of the simulation experiment are summarized in Table 3.7. The last column in the table represents a ratio of number of times a centre initiated dispatching rule is invoked to the number of times a vehicle initiated dispatching rule is invoked. Centre initiated dispatching implies that there are multiple idle vehicles in the system and one of them is to be selected for pickup assignment of an awaiting job. Such a rule which is adopted in the present experimental setup is nearest vehicle (NV) rule. On the other hand, vehicle initiated dispatching is invoked when an idle vehicle is to pickup one among multiple number of jobs awaiting pickup assignment. Earliest job arrival time (EJAT) is the

rule which is implemented here. The ratio of the two vehicle dispatching mechanisms denotes the relative importance of each of them. Discarding the results of the first shift in order to allow for warm-up period and transient behaviour of the system, the throughputs, vehicle activity times, and vehicle dispatching ratios of the last four replications are averaged.

Looking at the Table 3.7, it is observed that the throughput rate increases steadily as the fleet size is increased from 8 to 11 vehicles. The throughput increases at an approximately constant growth rate of 17 unit loads for each addition of an extra vehicle. Beyond a fleet size of 11 vehicles, the throughput rate stabilizes to nearly 190 unit loads per shift. This represents a saturation stage where nearly 95% of total number of jobs arriving in a shift get completely processed and depart from the system, or, in other words, nearly 95% of material handling needs are met. Increasing the fleet size beyond 11 vehicles does not produce significant increase in throughput rate.

Figure 3.5 shows the distribution of average of vehicle activity times and vehicle dispatching ratios when fleet size is varied. Vehicle activity time distribution shows a constant pattern as long as optimal fleet size of 11 vehicles is not reached. A vehicle spends approximately 55% of its time in load transfer and transport (state-I activities). Empty travel (state-II activity) accounts for its 41% of time approximately. On the other hand, waiting and blocking (state-III activities) take up negligibly small time. The ratio of empty travel time to load transfer and transport time comes to nearly 0.75, a figure which is closely approximated by the models of Beisteiner-II, Kuhn, and Kulweic. The proposed model also matches the figure, albeit on the under-estimation side. The models proposed by Maxwell, Beisteiner-I, and Koff give grossly under-estimated results, while Malmborg's model over-estimates the result.

There is an appreciable increase in idle waiting time of a vehicle beyond a fleet size of 11 vehicles. This is owing to the fact that the throughput rate has reached its maximum attainable under given conditions and a further rise in throughput rate cannot be expected by employing a fleet of more than 11 vehicles. Any vehicle added extra to the fleet will only result in increase in idle waiting time of the fleet since material handling requirements do not change. The increase in idle waiting

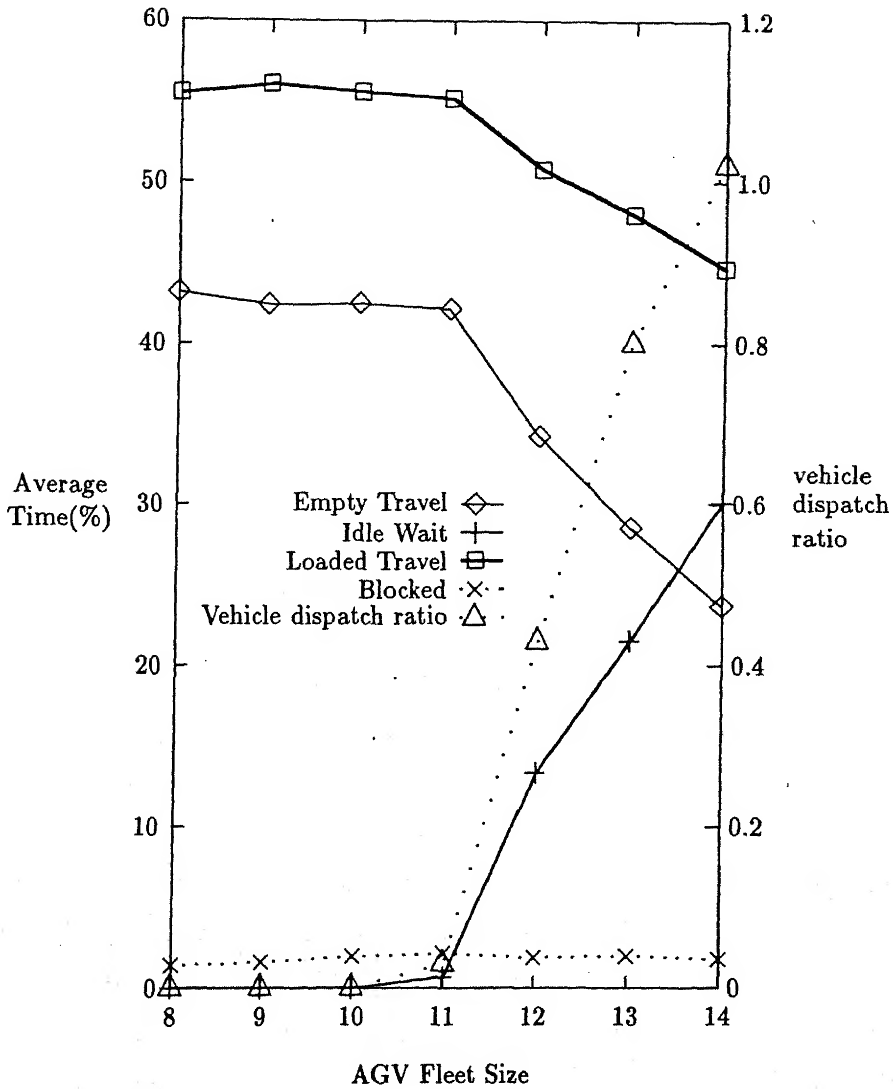

Figure 3.5: Distribution of vehicle activity time with fleet size

time is at the cost of decrease in loaded travel and empty travel times. Of these two, empty travel time shows a steeper decrease. This behaviour can be accounted for by the fact that when there are extra vehicles in the system, then likelihood of a centre initiated vehicle dispatching strategy increases. That is, now there are more chances of finding two or more idle vehicles at a given moment of time when a suitable vehicle is to be assigned the task of picking up an awaiting job. Invoking the nearest vehicle (NV) rule gives higher priority to a vehicle nearer to the job. As a consequence, vehicle's empty travel time may be reduced since the selected vehicle is nearer to the job than the other vehicle. Increase in relative importance of centre initiated dispatching to vehicle initiated dispatching beyond a fleet size of 11 vehicles is also evidenced by the trend of curve labelled "Vehicle dispatching ratio" in Figure 3.5. The value of the ratio is negligibly small till a fleet size of 11 vehicles. Beyond this size, there is a sudden rise in this ratio. This indicates that now there are more number of vehicles likely to be found idle at any given time, and centre initiated dispatching rule is going to be more often invoked into operation. Further discussion on vehicle dispatching strategies has been deferred to Chapter 5.

When the results of different analytical models are compared against the simulation results, it is observed that the models proposed by Beisteiner-II, Kuhn, and Kulweic over-estimate the required AGV fleet size by 1 vehicle. The proposed model under-estimates the requirement by 1 vehicle. Among these four models, the first three are more close to the simulation results in estimating the empty travel time.

A second case study in the above simulation experiment is conducted with an aim to study the variation between throughput rate and fleet size on account of varying job arrival rate. The mean of the Poisson job arrival process is varied from 40 unit loads per shift to 80, 120, 160, and 200 unit loads. The simulation results are summarized in Table 3.8 and plotted in Figure 3.6.

The trend of each curve in Figure 3.6 indicates that there is a steady growth in throughput rate vis-a-vis fleet size till the throughput reaches approximately 95% within the targetted throughput rate. Thereafter, a saturation stage is exhibited wherein throughput rate remains nearly same. The fleet size for this "knee point" in a throughput curve is a simulated estimate of optimal AGV fleet size. Such

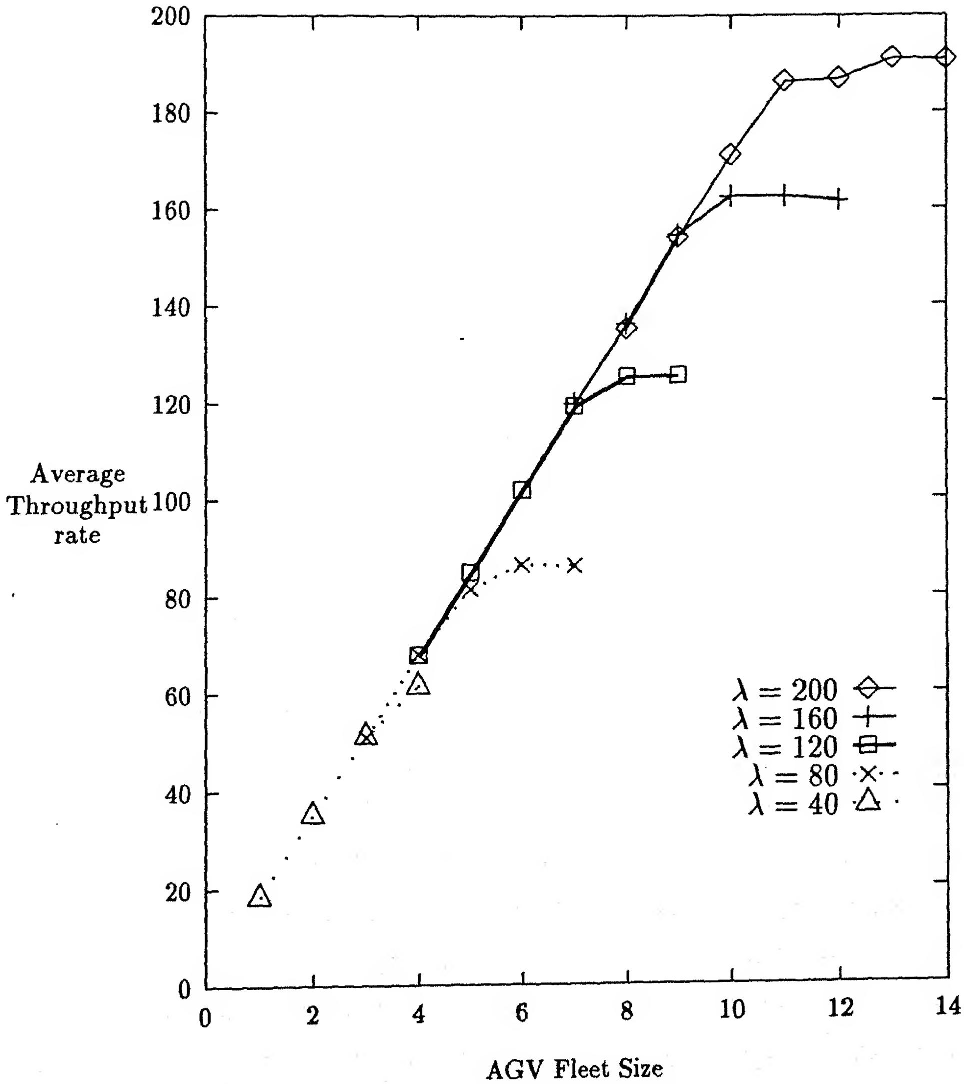

Figure 3.6: Variation of throughput and fleet size with job arrival rate

Table 3.8: Throughput and fleet size variation with job arrival rate

No of	Average throughput for job arrival rate				
AGVs	40	80	120	160	200
1	18.50				
2	35.25				
3	51.25	51.00			
4	61.50	68.00	67.75		
5		81.50	84.75		
6		86.50	101.75		
7		86.25	119.00	119.75	
8			125.00	136.00	135.00
9			125.25	154.50	154.00
10				162.50	171.00
11				162.50	186.25
12				161.50	186.75
13					191.00
14					190.75

optimal fleet sizes for different job arrival rates are then plotted on Figure 3.3. From that figure, it is observed again that the models presented by Beisteiner-II, Kuhn, Kulweic, and the proposed model give approximately same results as the simulation model. The models proposed by Maxwell, Beisteiner-I, and Koff under-estimate the vehicle requirement, whereas Malmborg's model over-estimates it.

As the last change in the above experimental setup, P/H ratio is varied for a constant job arrival rate of 200 unit loads per shift. P/H ratio, as an indicator to criticality of a resource, is changed from an earlier 3.107 (75:25) to 1.553 (60:40) and 1.306 (50:50). It implies that material handling resource is rendered more critical at each stage. The simulation results are summarized in Table 3.9.

It is observed that for P/H ratio of 1.553, 90% of the targetted output is reached with a fleet size of 23 vehicles. This figure is closely matched by the models of Beisteiner-II, Kuhn, Kulweic, and to a lesser extent by the proposed model. The result has also been plotted on Figure 3.4 . Shop locking phenomenon is exhibited by the system for P/H ratio of 1.306. When material handling resource is as critical as processing resource (50:50) then a larger fleet size is required to meet all the

Table 3.9: Throughput and fleet size variation with P/H ratio

No. of AGVs	Average throughput at P/H ratio 1.553	1.036
19	157.75	
20	164.75	
21	171.50	
22	175.25	
23	185.00	
24	187.75	
30		*
35		*
40		*

*Shop locking encountered

material handling needs, as estimated by different analytical models. However, with so many vehicles operating on the shop floor, likelihood of vehicle blocking increases. In fact, now the actual critical resource in the system is the existing guide path network. It is because of heavy traffic congestion at most of the locations in the network that production is brought to a standstill. Further discussion on shop locking phenomenon has been deferred to Chapter 5.

3.8 Conclusions

Determination of optimal AGV fleet size for an AGVS is a vitally important design issue. It has bearing on economic feasibility and justification of an FMHS to be employed in an FMS environment. Modelling the operational behaviour of such a system is a difficult task because of the presence of multiple decision variables whose interactions and performance impacts are difficult to predict without a detailed simulation analysis. However, simulation analysis cannot be performed exhaustively over a larger set of decision variable combinations. A need exists to make intelligent estimates of the decision variables prior to the simulation phase.

This chapter incorporates development of an analytical methodology for determination of optimal AGV fleet size. Total load handling (transfer and transport) time of vehicles is determined from given job parameters. Total empty travel time is estimated through various models reported in the literature. A new model is proposed for this purpose. Vehicle idle waiting and blocking times are discussed.

The analytical techniques presented in this chapter can be used to make good initial estimate of vehicle requirement independent of the timing of requirement at various location points. This helps in reducing the complexity of the problem of determination of optimal fleet size, and provides a good starting point for further analysis using simulation of the modelled system.

Computer simulation is used in this chapter as the final phase of the overall methodology of estimating vehicle requirement in the system. The primary aim of the simulation study is to perform a comparative evaluation of various analytical models vis-a-vis simulation model. Simulation is performed with the following objectives.

1. (a) To obtain a simulated estimate of optimal AGV fleet size for the AGVS under consideration.

   (b) To observe the distribution of vehicle activity times.

   (c) To study the relative importance of centre initiated vis-a-vis vehicle initiated vehicle dispatching mechanism.

   For this experimental setup, job arrival rate and P/H ratio are set constant.

2. To perform a load sensitivity analysis in the above experimental setup by varying the job arrival rate.

3. To study the effect of increasing the criticality of material handling resource on vehicle requirement.

Results of analytical models are compared with those of simulation model at each stage of the simulation experiment. The comparison shows that the models proposed by Beisteiner-II, Kuhn, Kulweic, and the proposed model estimate the vehicle requirement approximately same as the simulation model. Thus, the results

of these models can act as good initial estimate of fleet size requirement which can then be fine-tuned with a follow-up simulation study of the system.

Chapter 4

AGVS Flow Path Design

4.1 Introduction

Automated guided vehicle systems (AGVSs) continue to play a significant role in many low to medium flow manufacturing operations, including FMSs and other applications. The relatively inexpensive guide path which does not interfere with other material flow systems in the facility, coupled with the high degree of flexibility and control the system offers in vehicle routeing, has made AGVS a proven and viable material handling technology. The flow path layout for an AGVS is a critical component in the overall design of an FMHS that utilizes AGVs for material handling.

This chapter deals with the design of AGVS flow path and its operational features. The issues important for consideration in the flow path design are first discussed. The previous research work reported in the literature on analytical and simulation modelling of the flow path for an AGVS is then briefly reviewed. No research work has been reported pertaining to directly configuring an AGVS flow path along the lines of a hybrid (mixed) uni/bidirectional flow mode. A heuristic for this purpose is presented in this chapter. The hypothetical FMS of Chapter 2 forms the test facility. The heuristic is applied to the facility, and various alternate flow path designs are obtained. The design methodology of analytical modelling of a system to be followed up by a simulation modelling has again been followed in

this chapter. Section 4.4 details the simulation experimental setup. The objective is to study the throughput potentials of the test facility when it is operated on unidirectional, hybrid uni/bidirectional, and all-bidirectional flow path alternatives. An important decision variable considered in the study is the location and holding capacity of vehicle sidings required to minimize vehicle blocking times.

4.1.1 Issues in AGVS flow path design

The flow path network of an AGVS is defined by open aisles between machines, processing centres, departments, and fixed structures on the shop floor. It establishes the location and direction of the vehicle travel. Not only does it affect the total distance travelled by vehicles but also the vehicle requirement and space utilization. It has a direct impact on the operational performance of the system due to the degree of congestion induced by imbalances in the material flows at traffic intersections and other points of potential congestion.

A number of issues have to be considered while designing the flow path for an AGVS. These have briefly been discussed earlier in Chapter 1. Some important ones are addressed below.

Flow alternatives: The AGVS flow path design alternatives have been categorized in the literature as follows (Egbelu and Tanchoco 1982, 1986, Gaskins *et al* 1989, Tanchoco and Sinriech 1992, Bozer and Srinivasan 1989).

1. unidirectional flow,
2. bidirectional flow,
3. multiple lane flow,
4. mixed design consisting of the above three,
5. single loop recirculating flow, and
6. tandemly configured flow.

It is the unidirectional flow design that has been extensively implemented in various industry scenarios. Other design alternatives have remained more

of academic interest only. However, all of them have immense potentials of real life applications as the technological improvements are being continuously forwarded in software development, and also in vehicle design. Furthermore, all the design alternatives have practical applications in other traffic flow systems, viz., highways, streets, railroads, and communication networks (Agent and Clark 1982, Frank 1966, Petersen 1974, Weingarten 1958, Schwartz 1987). As a matter of progress in material handling technology, it is most natural that AGVS flow path design should also benefit from these established concepts and thus broaden the scope of flexibility of FMS.

Location of P/D stations: Closely interlinked with flow design is the issue of suitably locating the load P/D stations of a processing centre. In some design situations, options exist as to where to locate these sites within each centre. The location of load transfer stations is very important as they can significantly influence the traffic intensity on aisles, the distances between inter-centre P/D stations, and traffic control. On the whole, they affect system efficiency and consequently system cost.

Vehicle buffering areas: To resolve the traffic congestion in the system, consideration is to be given to temporal vehicle buffering zones. Provisions have to be made regarding locations of vehicle staging areas (parks) and battery charging points, and location and holding capacity of vehicle sidings for managing vehicle blocking phenomenon. The last mentioned aspect is specially manifested for the case of bidirectional flows where vehicles could be heading into each other. To resolve deadlock, one of the vehicles is selected for buffering in order to clear the track for the passage of the other. Thereafter, the buffered vehicle is released back onto the main track to continue its journey.

4.2 Literature review

In an AGV based MHS, the layout and orientation of the guide wire system dictate the direction of traffic flow in any given aisle as well as the traffic intensity in each

aisle. Several layout and guide wire orientation alternatives can be adopted. These alternatives are discussed below.

4.2.1 Unidirectional flow design

Unidirectional flow results when vehicles are restricted to travel only in one direction along a given segment of the guide path. This design is extensively implemented since unidirectional flows reduce the possibility of vehicle blocking, require fewer controls, and are more economical and aesthetically appealing (Egbelu and Tanchoco 1982). The disadvantage is the lack of flexibility which can in turn, result in longer vehicle trip times.

Gaskins and Tanchoco (1987) were the first to address the problem of finding a unidirectional flow path with an aim to minimize total loaded vehicle travel time (state-I activities), when vehicles are assumed to take shortest routes among various pairs of location points. They constructed a node-arc network out of the given guide path and formulated a non-linear integer programme (later converted to 0–1 programme). The constraints were in the form of — unidirectional flows, reachability of each node or a group of nodes, non-sinkability of each node or a group of nodes, and shortest vehicle routes.

Goetz and Egbelu (1990) built their model upon the contribution of Gaskins and Tanchoco (1987). They addressed the same problem using the same methodology. However, they differed in their analysis from that of Gaskins and Tanchoco (1987) on three fronts. Firstly, they developed a heuristic to seek out only major flows from each department in order to reduce the size of the problem to be solved. Secondly, they also considered a decision to uniquely locate the load P/D sites for each department. And thirdly, they exploited the structure of the problem to further reduce the number of constraints.

Usher *et al* (1988) and Rabeneck *et al* (1989) had also previously addressed the problem of selecting the flow path of an AGVS as well as locating load P/D stations simultaneously.

The problem of suitably locating load P/D sites was initially addressed by

Maxwell and Muckstadt (1982). They reasoned that empty vehicle travel is minimized if every segment (arc) of the network is balanced in the sense that the number of empty vehicles entering and stopping in the arc, and the number of empty vehicles beginning in and exiting the arc should not both be positive. Vehicle blocking can considerably be reduced if central aisles of the guide path network are used only as transit aisles. They further advocated a balance in workload among aisles in terms of P/D activity times and number of vehicles that load/unload. As much load transfer should be accomplished close to the warehouses as possible.

Kaspi and Tanchoco (1990) also tackled the same problem as presented by Gaskins and Tanchoco (1987). Recognizing that the previous model did not include the entire solution space and its inherent computational inefficiency, they proposed a follow-up model. In this expanded model, they added several other constraints and explicitly addressed the reachability problem. In addition, they described an efficient branch-and-bound technique which exploited the characteristics of the material flow matrix. They favoured implementation of this solution methodology because computational efficiency of 0–1 integer programming worsens as problem size grows for larger physical systems.

Sinriech and Tanchoco (1991) extended the work of Kaspi and Tanchoco (1990). They proposed an improved algorithm wherein only the intersection nodes of the network were included in the branch-and-bound algorithm. In addition, they included empty vehicle travels (state-II activity).

Sharp and Liu (1990) presented an analytical method for configuring the network of a fixed-path and closed-loop MHS. The objective was to make decisions with respect to shortcuts (cutbacks), off-line bypass construction, and bypass length. The solution presented by them indicated the location of off-line bypasses and shortcuts, the number of vehicles required and their recommended routeings, and the average flow in each part of the system.

Venkataramanan and Wilson (1991) presented an algorithm for determining the optimal unidirectional flow path for an AGVS with a given layout. The objective was to minimize the total (loaded and empty) distance travelled by vehicles subject to the constraint that the resulting network consists of a single strongly connected directed

graph. This constraint assured that a vehicle could leave any load P/D point in the facility, visit any other point, and return to the original point. The problem was based on the graph of the facility layout and graph theory properties. The method resulted in a linear objective function, required consideration of only a small number of relevant paths, and used the concept of strongly connected networks in place of the many sets of constraints as considered earlier by Gaskins and Tanchoco (1987). A specialized branch-and-bound algorithm was discussed in detail.

A major hurdle in designing the AGVS flow path with the aid of most of the above mentioned approaches is their computational complexity due to the nature of this combinatorial problem. Kouvelis *et al* (1992) developed five different heuristics for the design of unidirectional flow path for an AGVS, as well as developed simulated annealing algorithms. Their computational results indicated that a composite heuristic (i.e., one that combined the most successful of the five heuristics) yielded solutions of comparable quality in a fraction of the time required by simulated annealing. This became more valid in the case of large size flow path design problems where inaccurate estimates for the input data on empty vehicle trips existed.

4.2.2 Bidirectional flow design

The bidirectional design of flow path consisting of single switchable track is similar to the concept of reversible streets or single railroad track between terminals (Kavanaug and Dekay 1959). For each wire segment or aisle between intersections, traffic flow takes place in either direction, but vehicles are allowed to travel in one direction only at any time. Thus, when a bidirectional arc is captured by a vehicle, the other vehicles are allowed to enter the arc only in the direction of motion of traffic. Otherwise, the new vehicle must wait for clearance of upstream traffic in the arc. This traffic pattern requires that some facilities exist at the intersections of the arcs for temporary parking of the vehicles. When an approaching vehicle wants to use a bidirectional arc which is being used by another vehicle in the opposite direction, the vehicle moves into the parking place to wait for the right of way.

Egbelu and Tanchoco (1986) discussed three types of temporary parking places at a node — siding, spur, and loop. They studied the potentials of bidirectional traffic

flow by conducting a simulation experiment over two test facilities and comparing the throughput for bidirectional flow vis-a-vis unidirectional flow. Kim and Tanchoco (1993b) proposed an efficient algorithm for finding conflict-free shortest-time routes for vehicles moving in a co-ordinated manner in a bidirectional flow path AGVS. They presented simulation results to compare the performance of unidirectional and bidirectional flow systems.

Bidirectional flow paths are much robust and complex, presenting highly challenging traffic control problems. The distance travelled by vehicles in moving between points is reduced. Consequently, this improves the response time of the vehicles, thereby increasing the shop throughput. However, there is an added cost to be incurred in acquiring better control software and/or intelligent vehicles that make bidirectional flow possible. These controls are required for efficient traffic management of the system where vehicles, more frequently now than in unidirectional case, are involved in traffic congestions. Yet, the gain in productivity that results in the use of bidirectional flow can easily compensate for this added cost.

4.2.3 Multiple lane flow design

The multiple lane design concept is very similar to that used for major highways. There are two or more lanes in the same aisle because of heavy traffic requirement, though, each lane is essentially a unidirectional one. There is time/distance economy in vehicle travels. On the other hand, there is a lack of space economy, and high investment in guide wire layout and control software to manage intersection activities is required. With the advent of trackless guidance technologies and free ranging vehicles (Premi and Besant 1983), multiple lane flow design may become more promising than the bidirectional flow systems, and much more so than unidirectional case.

Gaskins *et al* (1989) extended the formulation of Gaskins and Tanchoco (1987). Their problem environment was designing of a virtual flow path system for free ranging AGVs with bidirectional tracks and multiple virtual lanes (tunnels) of vehicle flow. The model was built upon the multi-commodity transportation problem

and formulated as a mixed integer linear programme. The issues they addressed included the number of lanes of vehicle flow in each aisle and the direction of flow in each lane. Flow intensity along a lane was restricted by the lane capacity.

Kim and Tanchoco (1993a) suggested a methodology for designing multiple lane flow paths. They formulated an economic model (0–1 integer linear programme) which considered the construction cost of each path segment as well as the travel cost. An efficient branch-and-bound procedure was developed to determine the configuration of the flow path and the direction of each flow path segment.

4.2.4 Single loop recirculating flow design

Egbelu and Tanchoco (1982) suggested a single loop AGVS flow path configuration. They defined a loop as a fixed sequence of processing centres that vehicles visit and called it a Sequential Vehicle Dispatching (SVD) strategy (see Chapter 5). The motivation for using such a configuration was the simplicity of the traffic control algorithms and the elimination of the shop locking possibility. They, however, did not suggest any methodology for finding such a loop. Although not motivated by the guide path design problem, Bartholdi and Platzman (1989) used the single loop assumption to derive analytical results for the AGVS control problem.

Tanchoco and Sinriech (1992) presented a procedure, OSL (Optimal Single Loop), for designing an optimal single loop flow path for a given facility layout. The goal of the procedure was to find best single loop flow path and to locate load P/D stations along the loop so that the flow of parts in the system is minimized. Sinriech and Tanchoco (1992b) further showed that by using the single loop flow path configuration, some of the dynamic features of the system, like the impact of empty vehicle flows on the system performance, are reduced. Sinriech and Tanchoco (1993) also suggested faster and more efficient methods for solving the problem of design of an OSL.

4.2.5 Tandem configuration flow design

Bozer and Srinivasan (1989) proposed a radically different and quite promising design approach for configuring the AGVS flow path. Their system, called tandem configuration, stems from the need of keeping the system simple and is based on "divide and conquer" principle. In the traditional AGVS, each AGV can pickup a load from any station and deliver it to any other station, i.e., each AGV has access to all stations. The tandem configuration partitions all the stations into non-overlapping, single vehicle closed-loops with additional load P/D stations provided as an interface between adjacent loops. The system eliminates vehicle blocking/congestion and simplifies traffic control and management. The cellular manufacturing (GT) principles and distributed processing can effectively be implemented as each loop becomes a natural control component. There is an ease of modular expansion. The limitations of tandem configuration are that a unit load may require to be handled by more than one vehicle before it reaches its final destination, thus increasing material handling distance and time. Additional aisle space, guide path and interfacing load P/D stations have to be provided. The system is less flexible in tolerating vehicle breakdowns. Unbalanced loops in terms of workload can result into bottlenecks.

Bozer and Srinivasan (1991) further developed an analytical model to study the throughput performance of a single vehicle loop. The resulting expressions provided the first closed form analytical expressions to determine the throughput capacity of a single vehicle operating under a First Encountered First Served (FEFS) dispatching rule in a non-deterministic environment.

Occena and Yokota (1991) used a modified tandem sector configuration in their research work. While there was still only one AGV serving the sector and the sector was a closed-loop, the AGV was not restricted to a fixed sequence route. It could traverse the shortest path between its current location and its intended destination using a combination of uni and bidirectional paths. This configuration, they reasoned, had characteristics which were desirable from a just-in-time (JIT) perspective which formed their problem environment.

Some of the important issues, from the point of view of designing a tandemly-configured AGVS, are the following.

1. Developing a partitioning algorithm which can enable the grouping of processing centres into single-vehicle loops while minimizing the number of loops and satisfying the transportation requirements.

2. Determining the location of interfacing load transfer stations with optimal buffer sizes.

3. Solving the load routeing problem (LRP). A load may be handled by several vehicles or loops before it reaches its destination. Additionally, each vehicle or loop in the system has limited capacity constraints. The LRP involves the task of scheduling the load to be transferred among loops with delivery sequences and quantities. Several factors may possibly affect this problem, such as the direction of the loops, the throughput capacities of the loops, the vehicle speed, the feasible routes of the load to be transferred, and the relative location among the centres. This problem is particularly concerned with routeing of the load rather than the vehicle (vehicle routeing problem — VRP). It also requires some thought in balancing the workload among loops so as to prevent bottlenecks.

Lin *et al* (1994) discussed the LRP issue in detail. They presented an analytical approach (linear programming) for determining load routes, and followed it up with a simulation study. They established that LRP affects the operational performance of the AGVS in terms of the queue length at each centre. Lin and Dgen (1994) further presented a task-list time window algorithm to find the shortest travel time between two locations which are situated in different loops.

Wang and Hafeez (1994) used stochastic Petri nets (SPN) to model conventional and tandemly-configured AGVS. The SPN models were solved for their different properties, and the performance of the two flow designs were evaluated and compared.

4.2.6 Vehicle buffering areas

Coupled with the problem of vehicle blocking is also the problem of suitably locating temporal vehicle buffering zones throughout the guide path to hold blocked vehicles.

The number of buffering areas designated to hold blocked vehicles and their holding capacities are themselves decision variables that depend on the applicable AGV fleet size, vehicle routeing strategy, flow path layout, and facility size. In an FMS environment, the location and design of vehicle buffering areas require a compromise of several factors including space economy, design simplicity, ease of vehicle control, and investment on guide wire and control system. Raju and Chetty (1993) conducted an extended-timed Petri net based simulation study of an FMS with one of the aims as determination of the holding capacity of battery charging stations and vehicle parking lots.

4.3 Hybrid uni/bidirectional flow path design

4.3.1 Problem identification

Configuring an AGVS guide path along any one of the different flow design alternatives is one of the most vital and necessary decision issues which has to be incorporated into the overall AGVS design and control methodology. It is evident from the literature review of the previous section that most of the academic work as well as industrial application has been done in favour of unidirectional flow design. This mode of traffic flow pattern is simplistic and aesthetic in design and facilitates much easier traffic management and control. Many analytical models have been proposed for configuring a given guide path network as a unidirectional flow path layout. These have been discussed in the previous section. On the other hand, bidirectional flow path layout has conceptually been thought of as a robust and effective design alternative in reducing material flow distances. For the same amount of material handling requirements, this pattern of traffic flow facilitates shorter vehicle journeys, thereby increasing system throughput rate and necessitating a smaller vehicle fleet size. However, traffic management and control issues have to be effectively tackled. A mathematical analysis is not needed for its configuration purpose since all existing arcs in the given guide path network are assumed to allow traffic in both directions, though in one direction only at a time. That is why most of the research work related to bidirectional flow design has concentrated on simulation

methodology. The purpose has essentially been to make a comparative evaluation between throughput potentials of unidirectional vis-a-vis bidirectional flow designs.

There has been no research work reported in literature, in the knowledge of the author, which pertains to the task of altering a given unidirectional flow path layout into a hybrid (mixed) uni/bidirectional network. The AGVS networks that have been designed and experimented upon have mostly been either unidirectional or bidirectional, but very few hybrid ones. Even the few hybrid networks reported are only case studies in simulation, rather than involving an analytical design effort. The present work is an effort in developing such a methodology. The emphasis is on finding a guiding technique for reducing material flow distances by selectively rendering certain unidirectional paths into bidirectional ones. This way not only the material handling distances are reduced and throughput rate is increased, but also fewer vehicles are required to meet the material handling needs. The next sub-section discusses the methodology.

4.3.2 Solution methodology

The primary objective of reducing material flow distances is met by configuring a certain selected unidirectional path as bidirectional one so that material flow in reverse direction consumes lesser time. In a unidirectional flow path layout, a path from P point of the ith centre to D point of the jth centre, denoted here as path(i–j), is essentially different from path(j–i). The two paths traverse through different sets of nodes and arcs. They may be of same or different lengths depending upon physical dimensional layout of the facility. If they are of different lengths (one being shorter than the other) and if there is a considerable amount of material to be moved to and fro between the centres, then the shorter path becomes a good candidate for being altered into a bidirectional path. This is precisely the basis on which alternative flow designs have been obtained in the present work.

The technique developed and presented here requires certain amount of information as input to the methodology. This includes information related to an existing unidirectional layout, material flow intensity among processing centres, and vehicle travel time matrix for the given setup. Structure of material flow matrix can be

exploited to aid in the process of selecting one unidirectional path, among the many existing paths, which is to be configured as bidirectional one. The quantity f_{ij} of the flow matrix discussed in Section 3.3 denotes the amount of material to be moved from P point of the ith centre to D point of the jth centre, due to a unit flow at the receiving/shipping centre. On the other hand, f_{ji} represents material flow from the jth centre to the ith centre. The sum $f_{ij}+f_{ji}$ indicates the total quantity of material to be moved to and fro between the two centres. When different quantities in the **F** matrix are summed up for different (i, j) pairs of centres, then the maximum of all such sums represent a pair of centres between which maximum amount of material is to be transferred. If the shorter path between this pair of centres is made bidirectional then appreciable reduction in material flow distances is likely to expected. However, a simple additive function of the two quantities, f_{ij} and f_{ji}, may present the wrong side of the picture. The sum may be maximum among various other sums even if one of the two quantities is zero. Yet, such a case indicates a strong candidate for unidirectional rather than bidirectional path. In other words, if either f_{ij} or f_{ji} is zero, then the existing unidirectional flow structure between the two centres should not be altered.

The above discussion points to the use of a multiplicative rather than an additive function of the two quantities f_{ij} and f_{ji}. The product of the two quantities can be used as a criterion for selecting a path which is to be rendered bidirectional. Maximum value of this product, among various (i, j) pairs of centres, can be taken as an index for selectively rendering paths as bidirectional. Such an index has been used in the present work and forms the basis of a heuristic which is discussed below.

4.3.3 Proposed heuristic

Let S represent the set of all (i, j) pairs of processing centres in the given unidirectional flow path network. Material flow in the system occurs from P pont of the ith centre to D point of jth centre. If there are $C+1$ centres in the system (see notation of Section 3.3) all with co-located P/D points and if material flow within a centre is not considered, then there are exactly $C(C+1)$ members in the set S. Let the unidirectional path from P point of the ith centre to D point of the jth centre

be denoted by path$(i-j)$. The earlier used notations f_{ij} and t_{ij} represent the flow intensity and travel time respectively from P point of the ith centre to D point of the jth centre. The proposed heuristic consists of the following steps.

Step 0: Start

Step 1: Compute matrix **B** as follows.

$$b_{ij} = b_{ji} = f_{ij} \cdot f_{ji}, \ \ \forall (i,j) \in S.$$

Step 2: If $\mathbf{B} \equiv \mathbf{0}$, go to step 7, otherwise, find $b^*_{ij} = b^*_{ji} = \max(b_{ij})$, $\forall (i,j) \in S$. Let this maximum occur for (i^*, j^*) and (j^*, i^*) pairs in S. Ties can be resolved arbitrarily (in the illustrative example discussed in the next subsection, the ties have been considered simultaneously rather than being treated individually).

Step 3: if $t_{i^*j^*} = t_{j^*i^*}$, go to step 6, otherwise, let $t^* = \min(t_{i^*j^*}, t_{j^*i^*})$.

Step 4: t^* is associated either with path(i^*-j^*) or path(j^*-i^*). Let that path be denoted by path*.

Step 5: Configure all the unidirectional arcs contained within path* as bidirectional. Thus, one flow design alternative is obtained.

Step 6: Remove pairs (i^*, j^*) and (j^*, i^*) from S. Set $b_{i^*j^*} = b_{j^*i^*} = 0$. Go to step 2.

Step 7: Stop.

The following three observations can be made related to the above heuristic.

1. The heuristic works only when there are co-located P/D points in the system. If all the P/D points are situated at different locations, then matrix **B** (step 2) will be initially **0** and no hybrid flow design will be obtained.

2. If lengths of the two paths are equal (step 3), then no advantage is to derived out of making any one path bidirectional.

Table 4.1: **B** matrix

	1	2	3	4	5	6
1	–	0.05	0.05	0	0	0
2	0.05	–	0	0	0	0.025
3	0.05	0	–	0	0	0.025
4	0	0	0	0	0	0.025
5	0	0	0	0	–	0.025
6	0	0.025	0.025	0.025	0.025	–

3. The quantity f_{ij}, which has been used to derive matrix **B** (step 1), can be modified to include the impact of empty vehicle travel from D point of the ith centre to P point of the jth centre. Since vehicles travel from one centre to another not only carrying unit loads but also making empty trips, the inclusion of empty vehicle travel will result in a more realistic flow pattern among the centres. Thus, vehicle flow intensity rather than material flow intensity will be emphasized.

4.3.4 Illustrative example

The heuristic discussed in the previous subsection is applied to the hypothetical FMS of Chapter 2. Input information consists of the given unidirectional flow path layout (Figure 2.4), the flow matrix (Table 3.1), and the travel time matrix (Table 2.3). The aim is to obtain hybrid uni/bidirectional flow design alternatives out of the given layout so as to reduce overall material flow distances. The heuristic is applied in successive steps as follows.

1. Matrix **B** is first computed from the flow matrix. It is presented in Table 4.1.
2. The maximum element of **B** is 0.05 and it occurs for four (i,j) pairs. All of them are considered simultaneously rather than being treated separately. Thus,

   (a) $i^* = 1$ and $j^* = 2$,
   $t^* = \min(t_{12}, t_{21}) = 1.5$,

and path* = path(1−2).
Path(1−2) is made bidirectional.

(b) $i^* = 1$ and $j^* = 3$,
$t^* = \min(t_{13}, t_{31}) = 1.5$,
and path* = path(3−1).
Path(3−1) is made bidirectional.

As a result of the above mentioned two changes, a new flow design is obtained. The new travel time matrix and the flow path layout (hereafter referred to as Bi-I) are shown in Table 4.2 and Figure 4.1 respectively.

3. The next maximum element of **B** is 0.025 and it occurs for eight (i, j) pairs. Again, considering all of them at the same time, following modifications in the layout are obtained.

(a) $i^* = 2$ and $j^* = 6$,
$t^* = \min(t_{26}, t_{62}) = 3.5$,
and path* = path(2−6).
Path(2−6) is made bidirectional.

(b) $i^* = 3$ and $j^* = 6$,
$t^* = \min(t_{36}, t_{63}) = 3.5$,
and path* = path(6−3).
Path(6−3) is made bidirectional.

(c) $i^* = 4$ and $j^* = 6$,
$t^* = \min(t_{46}, t_{64}) = 1.5$,
and path* = path(4−6).
Path(4−6) is made bidirectional.

(d) $i^* = 5$ and $j^* = 6$,
$t^* = \min(t_{56}, t_{65}) = 1.5$,
and path* = path(6−5).
Path(6−5) is made bidirectional.

Table 4.2: Travel time matrix for Bi-I flow design

		To centre					
		1	2	3	4	5	6
	1	–	1.5	1.5	3.5	5.5	4.5
	2	1.5	–	2.5	2.5	4.5	3.5
From	3	1.5	2.5	–	4.5	6.5	5.5
centre	4	5.5	6.5	4.5	–	2.5	1.5
	5	3.5	4.5	2.5	2.5	–	3.5
	6	4.5	5.5	3.5	3.5	1.5	–

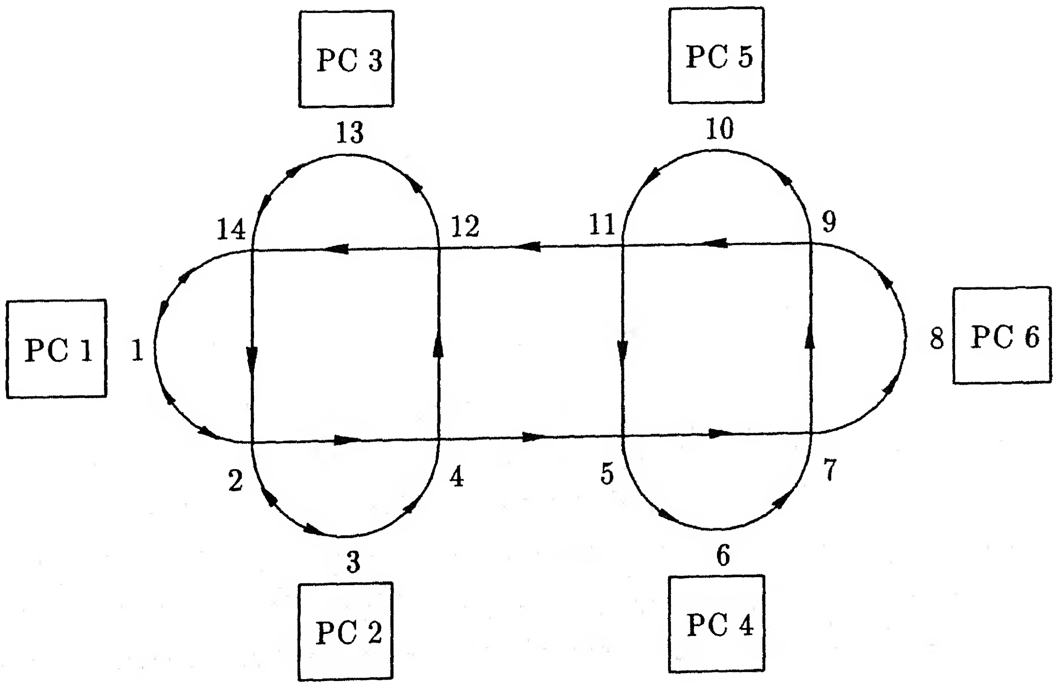

Figure 4.1: Bi-I flow path design

A new flow design is obtained as a result of these four changes made in the previously obtained Bi-I flow design. The new travel time matrix and the flow path layout (hereafter referred to as Bi-II) are shown in Table 4.3 and Figure 4.2 respectively.

The procedure is stopped here since there are no other elements in **B** for further consideration. It is to be observed that Bi-II flow design alternative is obtained from Bi-I flow design. If more number of alternative designs are required to be obtained, then the procedure which has been used for obtaining Bi-II design can be applied to the original unidirectional flow path design (hereafter referred to as Uni). Moreover, each set of pairs (i^*, j^*) and (j^*, i^*) can be taken up individually to obtain more number of alternative designs.

Finally, an all-bidirectional flow design (hereafter referred to as Bi-III) is obtained by altering all paths of Uni as bidirectional. The travel time matrix and the flow path layout for Bi-III are shown in Table 4.4 and Figure 4.3 respectively.

■ *Optimal fleet size*

The problem of determining optimal AGV fleet size for a given manufacturing scenario has been discussed at length in Chapter 3. Various analytical models described in that chapter are applied here on the four flow alternatives, viz., Uni, Bi-I, Bi-II, and Bi-III. The results are tabulated in Table 4.5 and plotted in Figure 4.4

These results again show the optimizing effect of the analytical models presented by Beisteiner-II, Kuhn, Kulweic, and to a lesser extent by the proposed model. The models proposed by Maxwell, Beisteiner-I, and Koff under-estimate the amount of empty travels made by the vehicles, resulting in lower fleet sizes. On the other hand, Malmborg's model estimates larger fleet sizes on account of over-estimation of empty travels. The figure also shows the simulation results which are discussed in the next section.

Table 4.3: Travel time matrix for Bi-II flow design

		To centre					
		1	2	3	4	5	6
From centre	1	–	1.5	1.5	3.5	5.5	4.5
	2	1.5	–	2.5	2.5	4.5	3.5
	3	1.5	2.5	–	4.5	6.5	3.5
	4	5.5	6.5	4.5	–	2.5	1.5
	5	3.5	4.5	2.5	2.5	–	1.5
	6	4.5	3.5	3.5	1.5	1.5	–

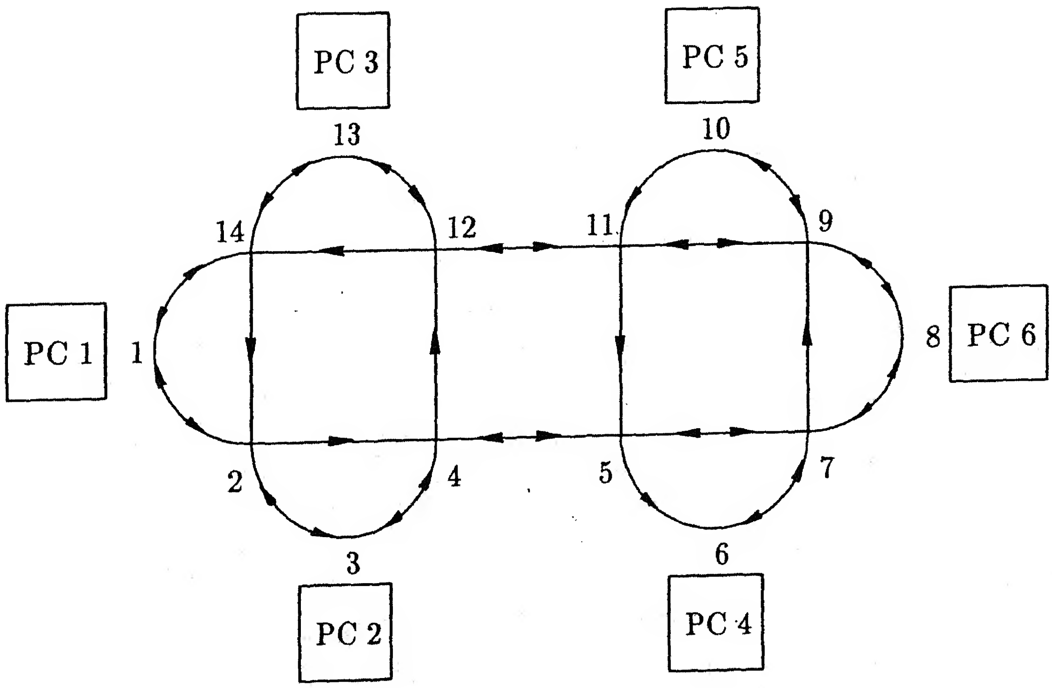

Figure 4.2: Bi-II flow path design

Table 4.4: Travel time matrix for Bi-III flow design

		To centre					
		1	2	3	4	5	6
	1	–	1.5	1.5	3.5	3.5	4.5
	2	1.5	–	2.5	2.5	4.5	3.5
From	3	1.5	2.5	–	4.5	2.5	3.5
centre	4	3.5	2.5	4.5	–	2.5	1.5
	5	3.5	4.5	2.5	2.5	–	1.5
	6	4.5	3.5	3.5	1.5	1.5	–

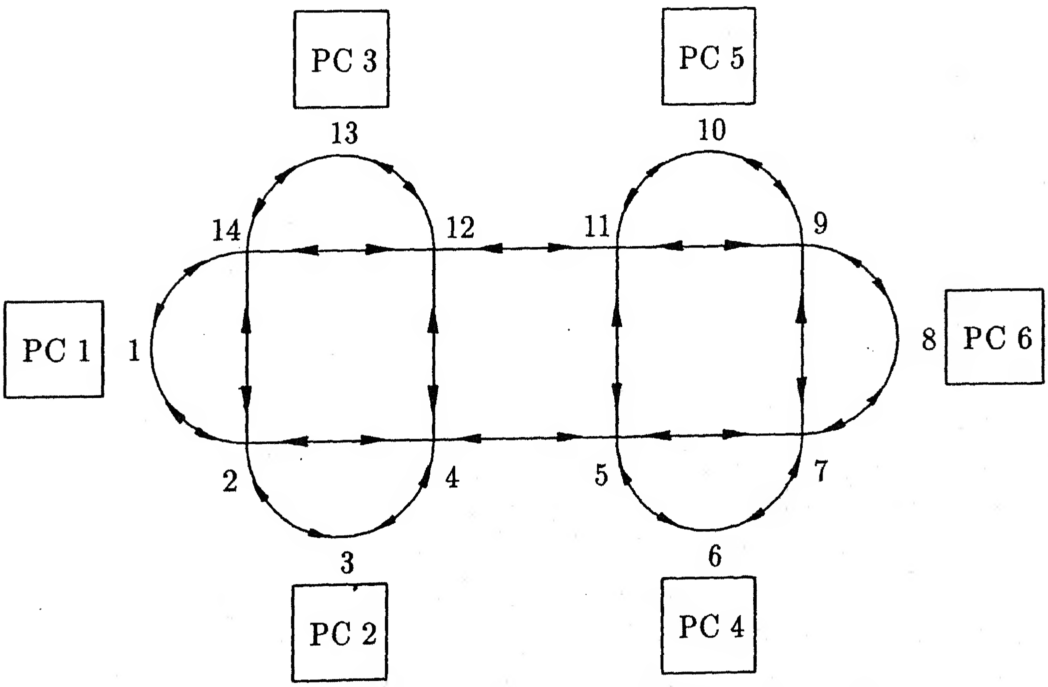

Figure 4.3: Bi-III flow path design

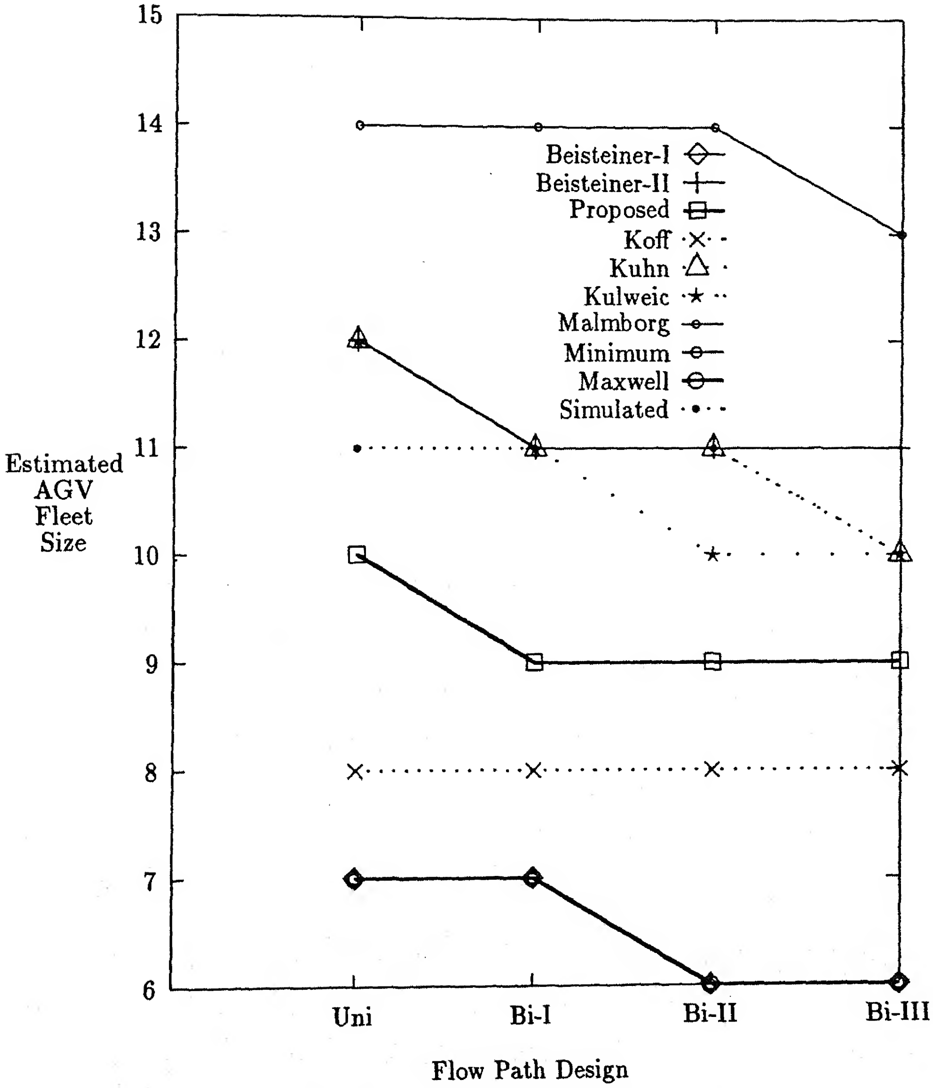

Figure 4.4: Estimation of AGV fleet size for various flow path design alternatives

Table 4.5: Estimation of AGV fleet size for various flow designs

Model	Estimated fleet size Uni	Bi-I	Bi-II	Bi-III
Minimum	7	7	6	6
Maxwell	7	7	6	6
Beisteiner-I	7	7	6	6
Beisteiner-II	12	11	11	11
Kuhn	12	11	11	10
Koff	8	8	8	8
Kulweic	12	11	10	10
Malmborg	14	14	14	13
Proposed	10	9	9	9

4.4 Simulation study

The simulation experiment for the hypothetical FMS of Chapter 2 is carried out with the following objectives related to AGVS flow path design.

1. The principal aim of this simulation study is to compare the productive potentials of the hypothetical FMS when it is operated either on unidirectional mode (Uni), or various hybrid uni/bidirectional modes (Bi-I, Bi-II), or all-bidirectional mode (Bi-III). The objective is to see the effect of reduction in material flow distances, and bidirectionality of paths on the system throughput rate and optimal fleet size. Hybrid uni/bidirectional flow designs are obtained by applying the proposed heuristic discussed in the previous section.

2. The second aim of the simulation study is to observe the distribution of vehicle activity time under different flow design scenarios. As a result of rendering certain paths as bidirectional, the likelihood of vehicle blocking increases. Though, fewer vehicles may be required on account of reduction in material flow distances, vehicles may be consuming more time for resolution of vehicle interference and conflict. Simulation methodology is helpful in studying such operating behaviour of the system.

3. One of the operational problems to contend with, specially in a bidirectional flow system, is how to resolve vehicular conflicts in the use of an aisle. Such conflicts generally arise when two sets of vehicles travelling in reverse direction desire to use an aisle. For the purpose of managing vehicular congestion/blocking phenomenon, temporal vehicle buffering areas capable of holding blocked vehicles are assumed in the network. These buffering zones are present in the form of vehicle sidings at the end of each arc terminating in a node. Thus, a unidirectional arc has a vehicle siding only towards its head node, whereas a bidirectional arc is assumed to have vehicle sidings towards its both head node and tail node. The third aim of this study is to determine, through simulation, the holding capacity of each vehicle siding so that the shop is not locked because of vehicle blocking and interference. Shop locking phenomenon due to vehicle blocking may be manifested, specially in the bidirectional flow system, when no provisions are made for vehicle buffering facility, or when no intelligent methods are employed for diverting the blocked vehicles to other less congested arcs. In the absence of any vehicle buffering facility, the vehicles cannot pass or cross each other at any node while heading into each other. Once the vehicle movement is arrested at a node, the effect is propagated progressively to other nodes and soon the vehicular movements are brought to a standstill in the whole shop. None of the empty vehicles dispatched for load pickup or delivery or the loaded vehicles heading for load delivery can get to its destination due to interferences from other vehicles. Further discussion about shop locking phenomenon and its remedial measures has been deferred to Chapter 5. In the present study, the holding capacity of a vehicle siding has been treated as a decision variable and is determined via simulation methodology.

Experimental conditions for the simulation include the following.

1. Mean of the Poisson job arrival process = 200 unit loads per shift.

2. P/H ratio = 3.107.

3. Processing centre data, as given in Table 2.1.

4. Job parameters, as given in Table 2.2.

5. AGVS networks and vehicle travel time matrices, as discussed in the previous section.

6. Vehicle initiated dispatching rule = EJAT.

7. Centre initiated dispatching rule = NV.

8. Job scheduling rule = FCFS.

9. Vehicle traffic rule at nodes = FCFS.

10. Static vehicle routeing.

The simulation experiment is carried out for a time period of five shifts resulting into five independent replications of one shift each. Results of the first shift are again discarded in order to account for cold-start of the system. Results of the remaining four shifts are averaged out. The averages are observed to lie within 90% confidence intervals. Technique of common random numbers is used for variance reduction in output results. The following sub-sections give the details of the three case studies.

4.4.1 Throughput performance

The aim of the first case study, as discussed earlier, is to make a comparative evaluation in throughput potentials of the system when it is operated under different flow design alternatives. Results of the simulation experiment are summarized in Table 4.6 and depicted in Figure 4.5.

It is observed from these results that nearly 93% of the throughput target is met when the fleet size is 11, 11, 11, and 10 vehicles respectively for Uni, Bi-I, Bi-II, and Bi-III flow designs. This shows that one vehicle is required less when switching over from unidirectional flow mode to all-bidirectional one. The hybrid flow designs do not offer any advantage in terms of reducing fleet size. However, below the optimal fleet sizes, there is a significant difference in throughput potentials of the four flow designs. For instance, if 9 or 10 vehicles are employed, then higher throughput rate

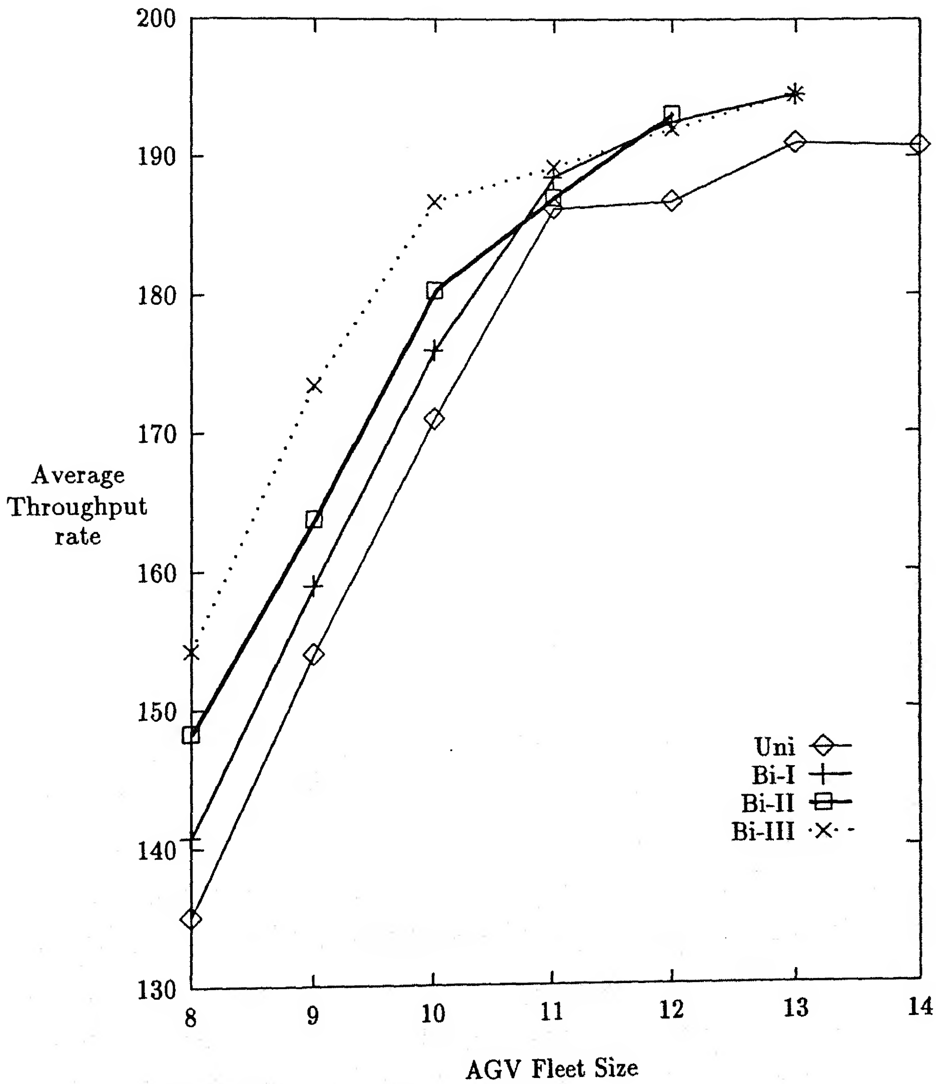

Figure 4.5: Throughput rate for various flow path design alternatives

Table 4.6: Throughput rates (unit loads per shift) for various flow designs

No. of	Average throughput rate			
AGVs	Uni	Bi-I	Bi-II	Bi-III
8	135.00	140.75	148.25	154.25
9	154.00	159.00	163.75	173.50
10	171.00	176.00	180.25	186.75
11	186.25	188.50	187.00	189.25
12	186.75	192.50	193.00	192.00
13	191.00	194.50	*	194.50
14	190.75			

* Shop locking encountered

is expected to be achieved by increasing the amount of bidirectionality in the AGVS network. As more number of paths are configured bidirectional, higher throughput rates are attained for the same number of vehicles in the system. This trend continues till a saturation stage sets in where throughput rate does not increase appreciably with addition of extra vehicles. Such "knee points" occur at 11, 11, 11, and 10 vehicles respectively for Uni, Bi-I, Bi-II, and Bi-III flow designs. Beyond these optimal fleet sizes, the flow designs do not produce a significant variation in throughput rates.

All-bidirectional flow design (Bi-III) does not help in reducing material flow distances over the hybrid Bi-II flow design, since Bi-II flow design incorporates switching to bidirectional all the paths over which material flow occurs. And yet, Bi-III flow design has a higher throughput potential than Bi-II flow design. This is accounted for by the fact that vehicles have to make empty trips too, besides loaded trips. Since Bi-II flow design contains a few paths which are still unidirectional, the vehicles, as a result, will be taking longer times to make empty trips. On the other hand, Bi-III flow design contains all the paths configured as bidirectional ones. Consequently, vehicles will take lesser time in executing empty trips. As a result, fewer number of vehicles will be required for attaining a given throughput target. Similarly, at a given fleet size the Bi-III flow design will result in higher throughput rate.

Table 4.7: Vehicle dispatching ratio for the four flow designs

No. of	Vehicle dispatching ratio			
AGVs	Uni	Bi-I	Bi-II	Bi-III
8	0	0	0	0
9	0	0	0	0
10	0	0	0.01	0.10
11	0.03	0.09	0.13	0.36
12	0.43	0.49	0.61	0.77
13	0.80	0.81	*	1.07
14	1.02			

* Shop locking encountered

Vehicle dispatching rules which are used in the simulation study of this chapter include EJAT (Earliest Job Arrival Time) and NV (Nearest Vehicle). The EJAT rule is a vehicle initiated dispatching rule which is invoked when a vehicle, after having delivered its load and acquired an idle status, is to be assigned next load pickup task. There are multiple jobs awaiting pickup at different locations. They have to be prioritized so that a suitable job may be matched with the vehicle. The EJAT rule awards highest priority to a job which arrived earliest into the system. On the other hand, when there are multiple idle vehicles at any given time in the system, and one of them is to be assigned the pickup task for a job which has been just then downloaded onto an output buffer, then a centre initiated dispatching rule is to be invoked. The rule prioritizes the vehicles to match the job. The NV rule has been used in this study. The relative importance of the two rules can be defined by a ratio of the number of times the NV rule is invoked to the number of times the EJAT rule is invoked (vehicle dispatching ratio of Section 3.7). A higher value of this ratio indicates a greater likelihood of finding an idle vehicle in the system. Table 4.7 and Figure 4.6 summarize the simulation results of this ratio for the four flow designs.

These results show that below the optimal fleet sizes, the value of this ratio is negligibly small for all the four flow designs. It means that vehicles are rarely idle so as to invoke the NV rule. All dispatching is governed by the EJAT rule. Beyond the

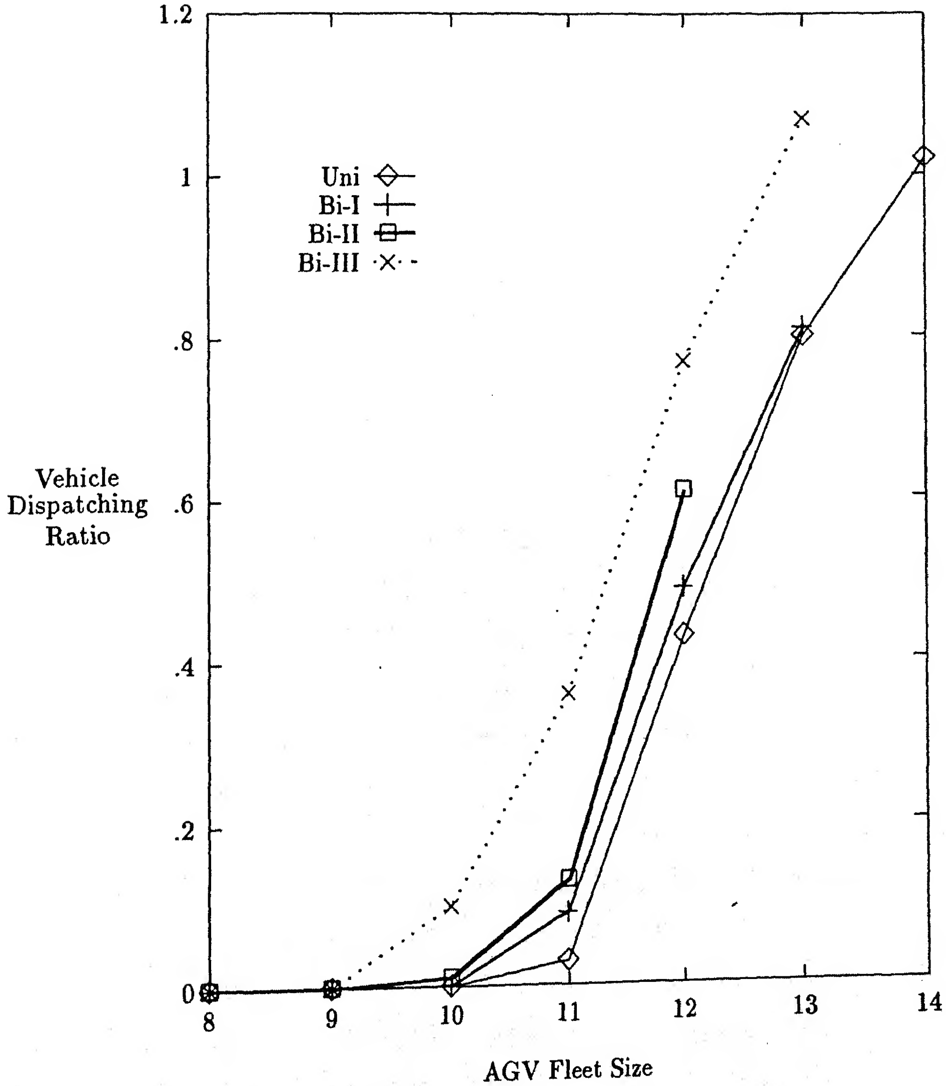

Figure 4.6: Vehicle dispatching ratio for various flow path design alternatives

optimal fleet size, there are more vehicles in the system than required. Likelihood of finding an idle vehicle thus increases and the NV rule gets opportunity to be invoked. The value of the ratio increases as additional vehicles are deployed. Hence, this ratio can be used to determine the number of vehicles required to meet the material handling needs of the system. From Figure 4.6, the optimal fleet sizes are found as 11, 11, 11, and 10 vehicles respectively for Uni, Bi-I, Bi-II, and Bi-III flow designs.

The optimal fleet sizes for various flow designs are plotted in Figure 4.4 along with results of various analytical models. It is observed that the models presented by Beisteiner-II, Kuhn, Kulweic, and the proposed model estimate AGV fleet size approximately same as that by the simulation model of the system.

4.4.2 Vehicle activity time distribution

The second case study involves studying the distribution of vehicle activity time. The measure of performance is the average percent time a vehicle spends in its different state activities. Results for the unidirectional flow design (Uni) have already been discussed in Chapter 3 (Table 3.7 and Figure 3.5). Results for the hybrid uni/bidirectional and all-bidirectional flow designs (Bi-I, Bi-II, and Bi-III) are summarized in Table 4.8 and depicted in Figures 4.7, 4.8 and 4.9 respectively.

The results shown in the above mentioned figures indicate a trend similar to that shown in Figure 3.5 for unidirectional flow design. The constant pattern of each curve lasts till an optimal fleet size is reached, after which there is a sudden increase in idle waiting time of a vehicle at the cost of decrease in its loaded travel and empty travel times. Analysis of the results for unidirectional flow design has been given in Section 3.7. The same explanation is applicable here also. There is no significant difference between the results for Uni and Bi-I flow designs at the optimal fleet size of 11 vehicles. A vehicle spends approximately 50–55% of its time in load handling, 40–42% in empty travels, 2–3% in blocked state, and the remaining time as waiting idle. This similarity in the vehicle activity time distribution for the two flow designs indicates that the unidirectional paths which have been converted into bidirectional ones do not reduce material flow distances significantly. However,

Table 4.8: Vehicle activity times for various flow designs

No. of AGVs	Vehicle activity time (%) Load handling	Empty travel	Waiting	Blocked
		Bi-I		
8	56.13	41.28	0	2.58
9	55.78	41.52	0	2.68
10	55.66	41.09	0.17	3.24
11	54.21	39.72	2.86	3.30
12	50.50	32.02	14.00	3.14
13	47.37	26.84	22.83	2.99
		Bi-II		
8	54.89	36.89	0	8.24
9	53.78	36.89	0	9.34
10	53.31	36.00	0.37	10.34
11	51.11	33.77	5.06	10.06
12	48.02	26.98	16.65	8.45
		Bi-III		
8	54.56	36.23	0	9.21
9	53.61	35.55	0	10.09
10	52.84	32.94	3.95	10.30
11	48.98	29.13	12.41	9.50
12	45.70	23.09	22.94	8.35
13	42.54	19.68	30.39	7.38

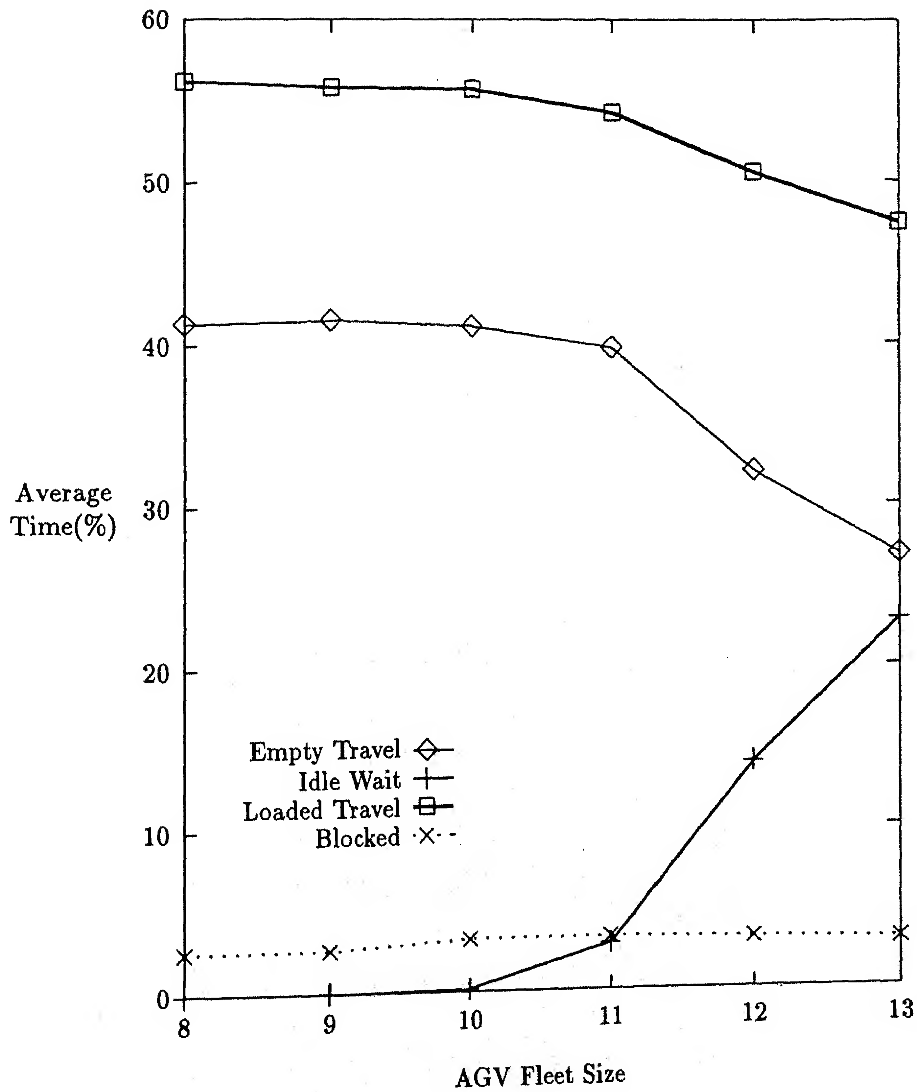

Figure 4.7: Distribution of vehicle activity time for Bi-I flow design

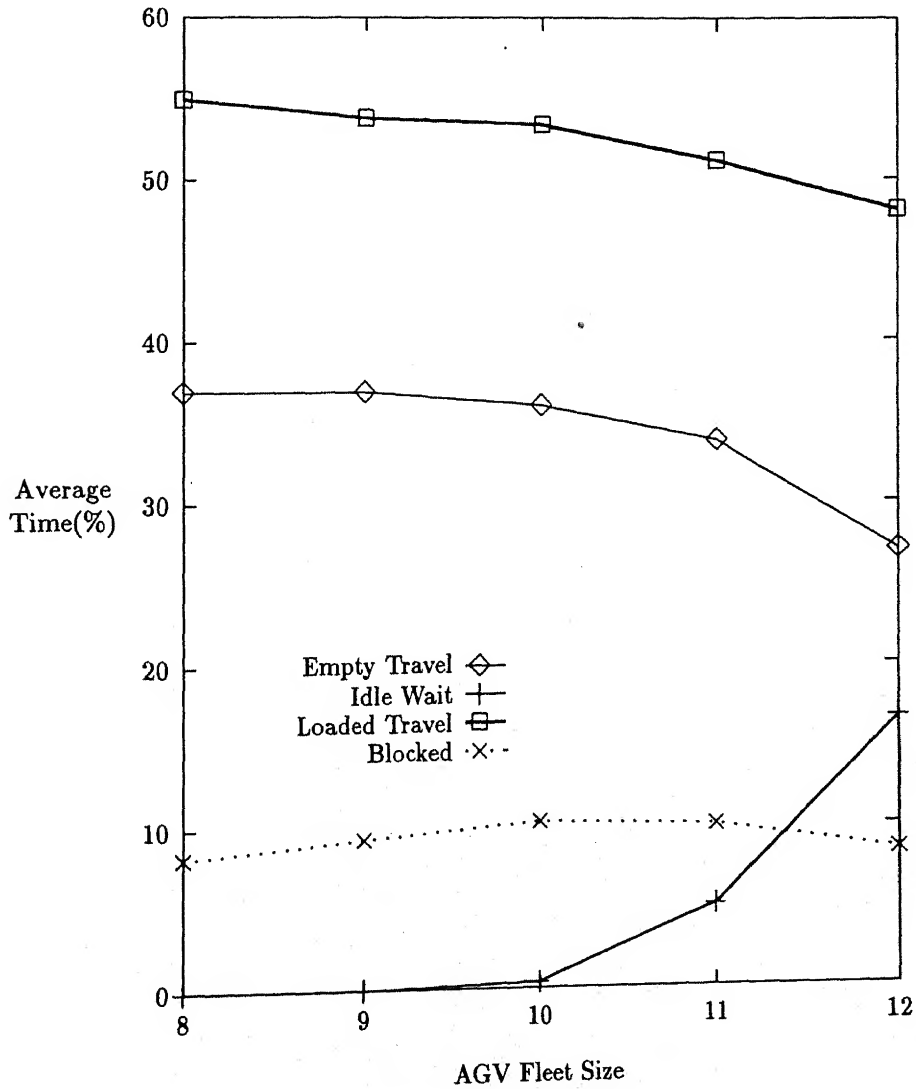

Figure 4.8: Distribution of vehicle activity time for Bi-II flow design

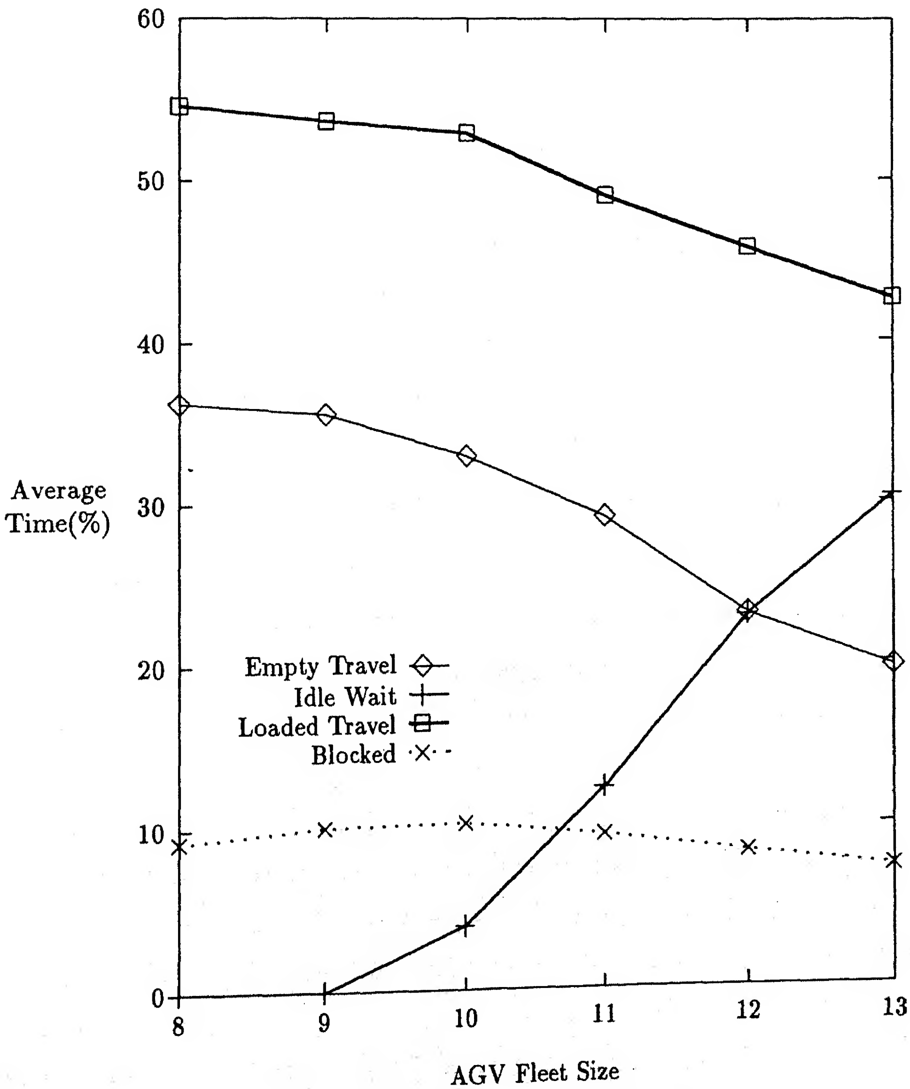

Figure 4.9: Distribution of vehicle activity time for Bi-III flow design

there is an appreciable difference in vehicle activity time distribution at the optimal fleet size of 11 vehicles when the flow mode is changed from Bi-I to Bi-II design (Figures 4.7 and 4.8). A vehicle now spends only 32% of its time in empty travels whereas it remains blocked for as much as 10% of its time. This shows that the cumulative effect of converting various unidirectional paths into bidirectional ones, as given in Bi-II flow design, has induced considerable amount of bidirectionality in the network. Thus, vehicles take shorter distance paths to their destinations. As a result, some of the paths become more congested than the others and traffic is heavier along them. Consequently, more vehicle time is wasted in resolving the traffic conflicts. The results for Bi-III flow design at the optimal fleet size of 10 vehicles are similar to those of Bi-II design at the optimal fleet size of 11 vehicles, though with minor variation. The impact of vehicle blocking phenomenon has further been analyzed in the third case-study presented below.

4.4.3 Location and holding capacity of vehicle sidings

The holding capacity of a vehicle siding is determined here as the maximum number of vehicles held simultaneously at that site at any time in the simulation run excluding the first shift. Since the primary objective is to maximize the shop throughput rate, the holding capacity of vehicle sidings is determined only for the case of optimal fleet sizes, i.e., when there are 11, 11, 11, and 10 vehicles in the case of Uni, Bi-I, Bi-II, and Bi-III flow designs respectively. Table 4.9 summarizes the simulation results pertaining to the requirement of vehicle buffering sidings in the network. The same results are plotted in Figure 4.10. Nodal locations of these sidings and their holding capacities for the four flow designs are depicted in Figures 4.11 to 4.24.

These results indicate that there is a considerable increase in the requirement of sidings both location-wise and capacity-wise when the flow mode is changed from Bi-I to Bi-II. Besides the P/D stations, all other locations (intersection points) have the necessity of sidings in various arcs connected to these nodes. Bi-II and Bi-III flow designs have similar requirements of sidings.

It is evident that though the hybrid and all-bidirectional flow systems improve the

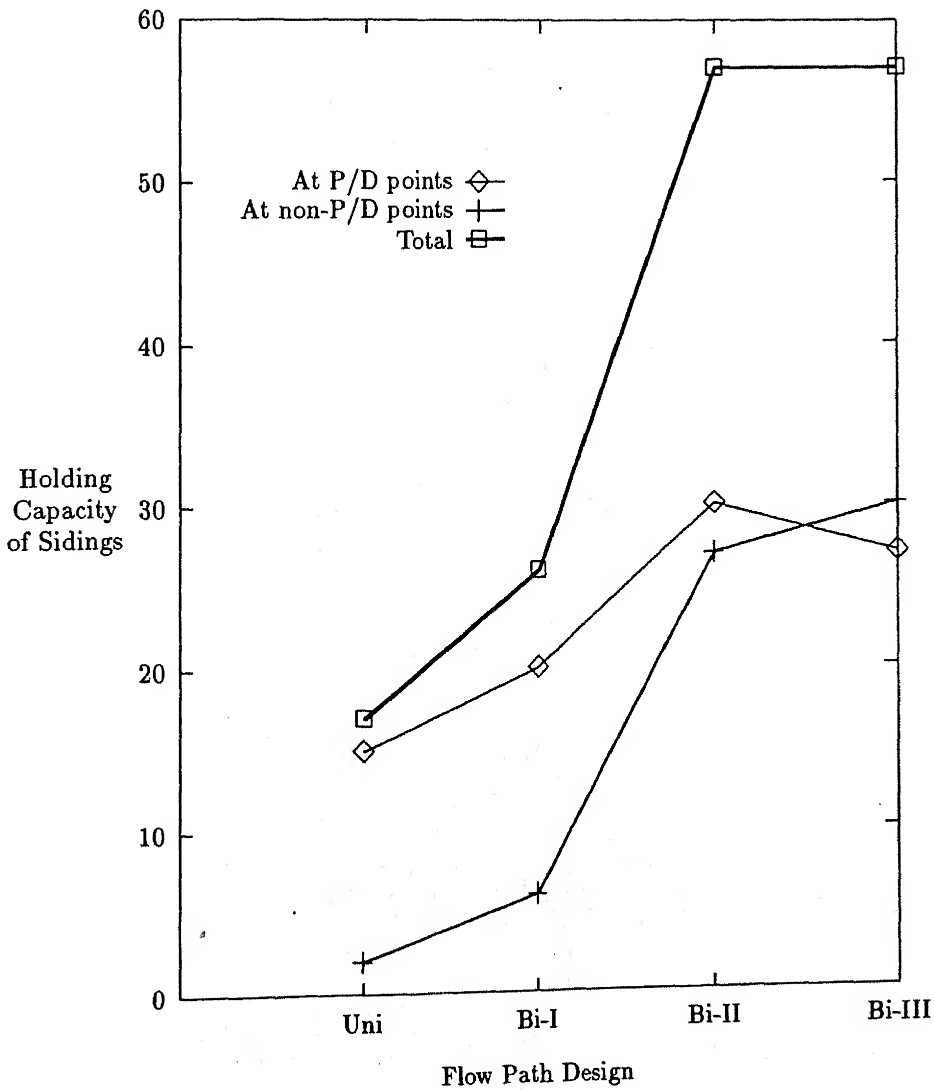

Figure 4.10: Holding capacity of vehicle buffering sidings

Table 4.9: Holding capacity of vehicle buffering sidings

Holding capacity of sidings	AGVS flow path design Uni	Bi-I	Bi-II	Bi-III
at P/D points	15	20	30	27
at non-P/D points	2	6	27	30
total	17	26	57	57

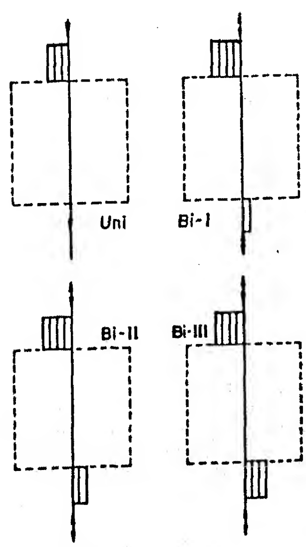

Figure 4.11: Holding capacity of vehicle sidings at node 1

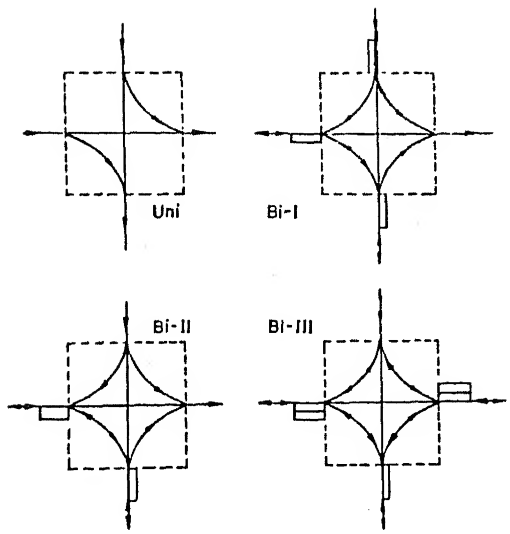

Figure 4.12: Holding capacity of vehicle sidings at node 2

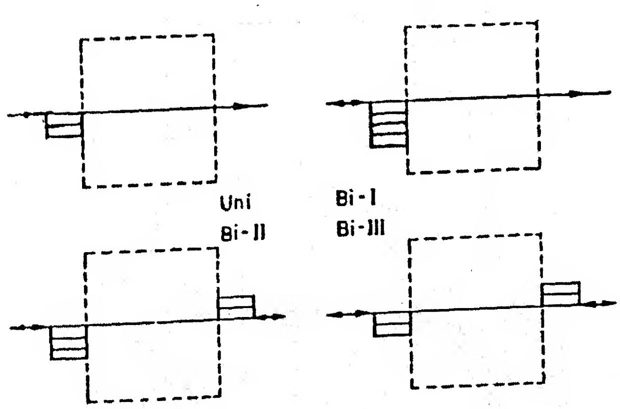

Figure 4.13: Holding capacity of vehicle sidings at node 3

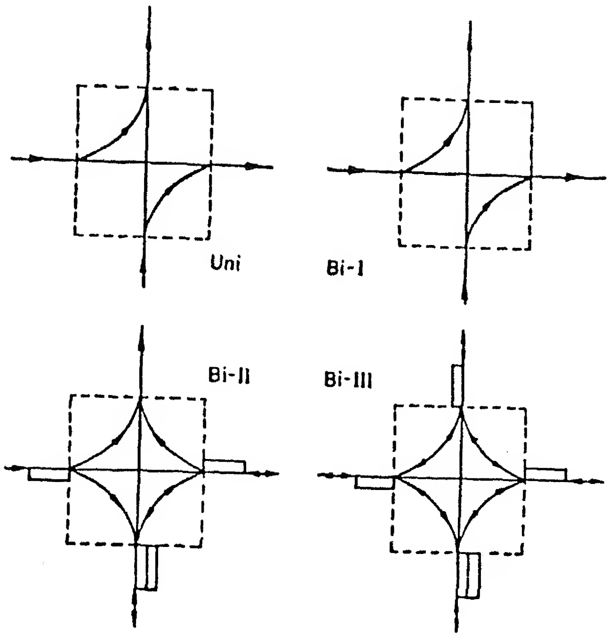

Figure 4.14: Holding capacity of vehicle sidings at node 4

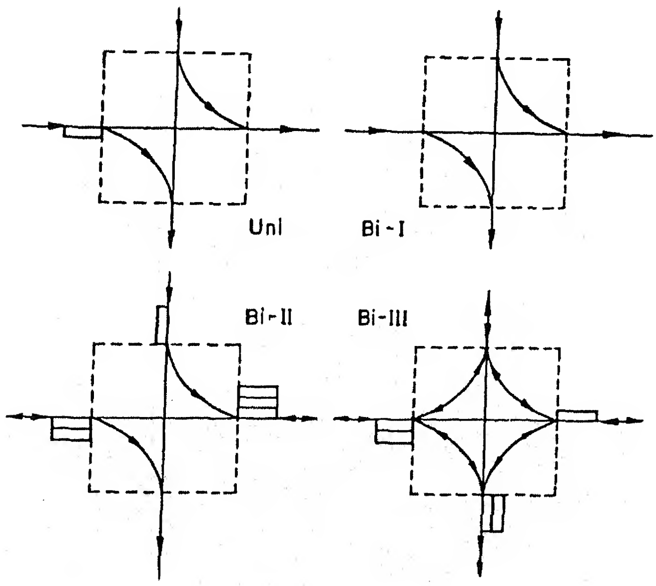

Figure 4.15: Holding capacity of vehicle sidings at node 5

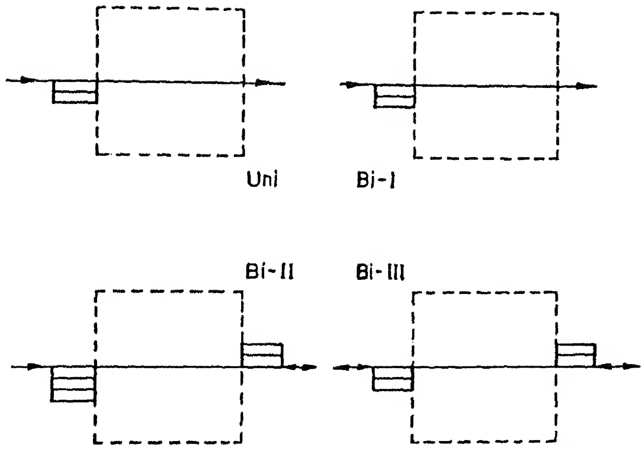

Figure 4.16: Holding capacity of vehicle sidings at node 6

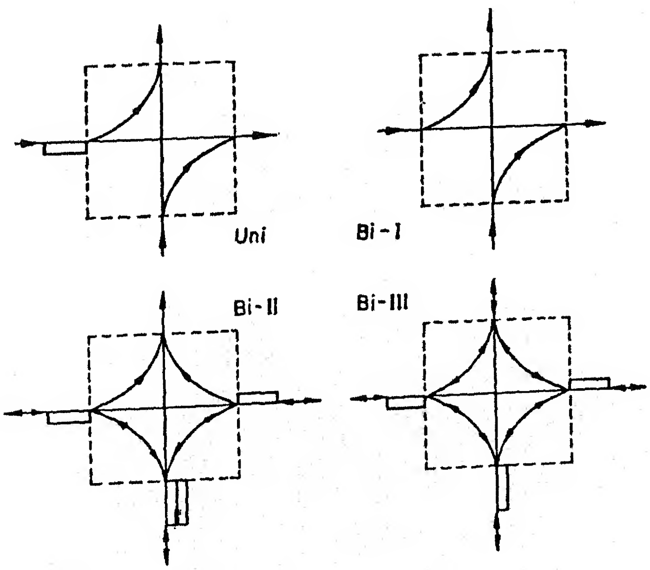

Figure 4.17: Holding capacity of vehicle sidings at node 7

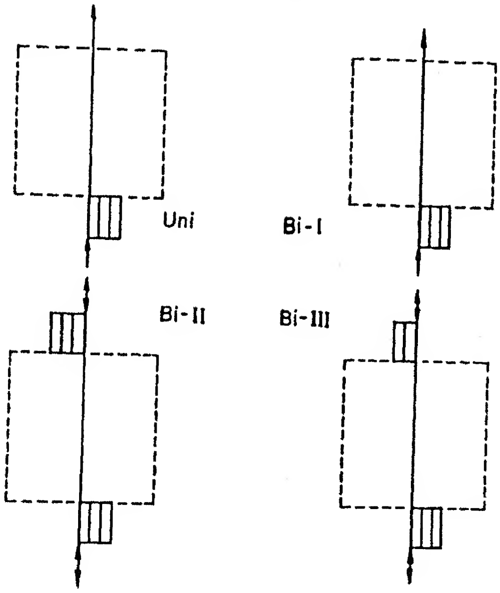

Figure 4.18: Holding capacity of vehicle sidings at node 8

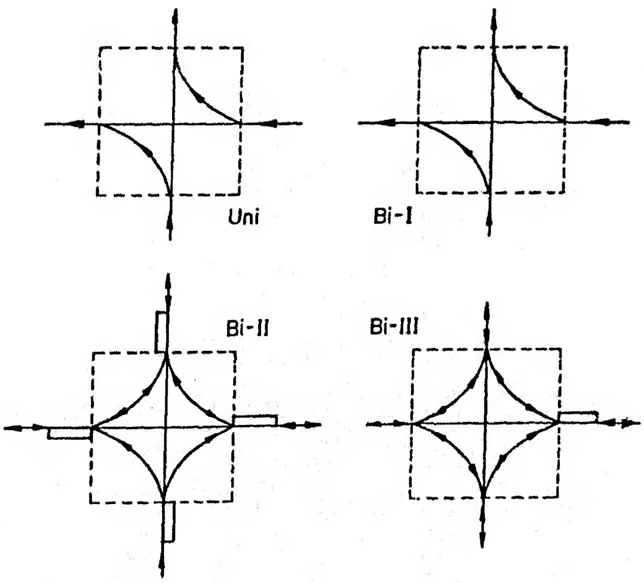

Figure 4.19: Holding capacity of vehicle sidings at node 9

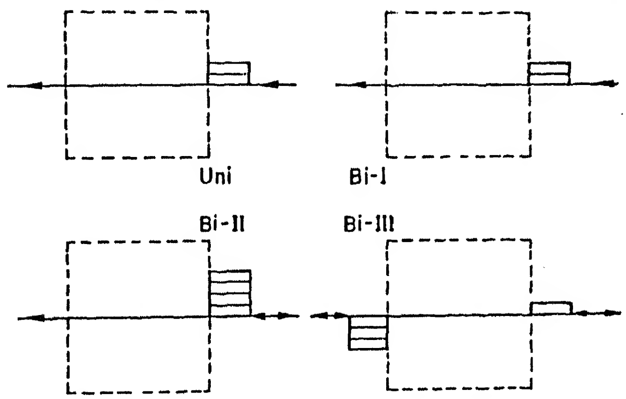

Figure 4.20: Holding capacity of vehicle sidings at node 10

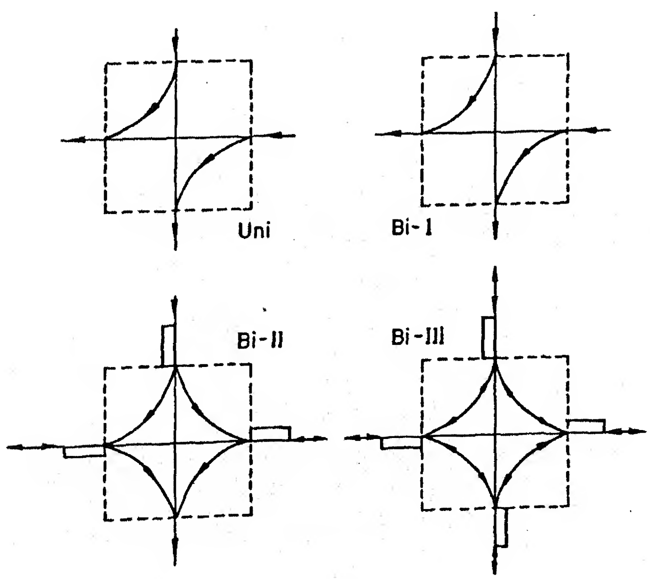

Figure 4.21: Holding capacity of vehicle sidings at node 11

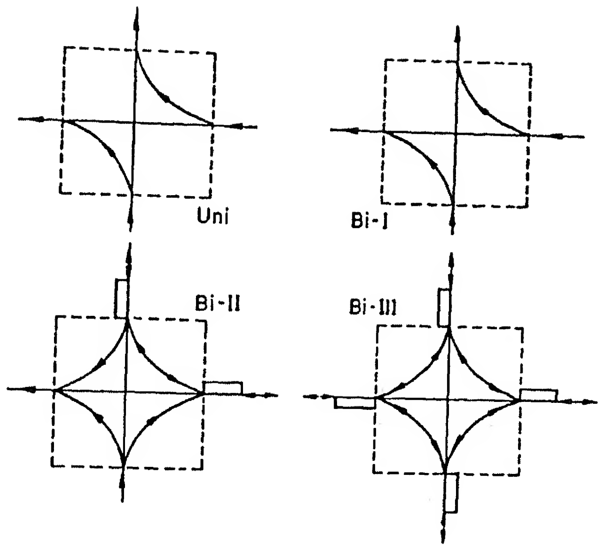

Figure 4.22: Holding capacity of vehicle sidings at node 12

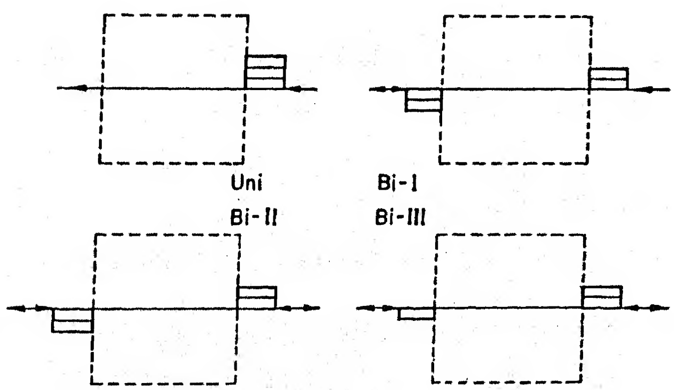

Figure 4.23: Holding capacity of vehicle sidings at node 13

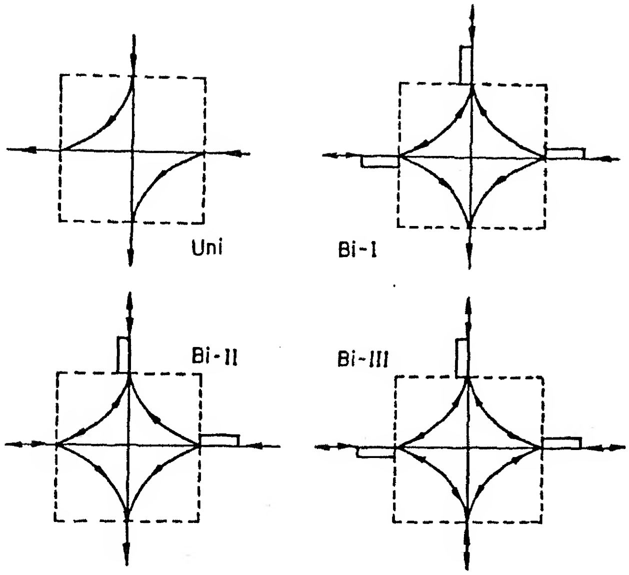

Figure 4.24: Holding capacity of vehicle sidings at node 14

shop throughput rate (with Bi-III requiring fewer vehicles), they can be successfully managed only when adequate vehicle buffering areas have been provided in the system. This involves additional cost in terms of guide wire layout for ramps and sidings, and sophisticated system controllers. Aisle space requirement is also increased at the nodes.

The estimates of vehicle buffering necessities presented above have been obtained through simulation study and lack any analytical modelling foundation. Moreover, they are strictly dependent on input parameters of the simulation programme. In totality, the number of locations designated as vehicle sidings and their holding capacities are dependent on many factors including the following.

AGV fleet size: More is the number of vehicles operating in an environment, more is the likelihood of their interfering with the planned routes of each other, and consequently more is the requirement of vehicle buffering areas.

AGVS flow path layout: Given everything else as same, in general, bidirectionality in the flow system involves more vehicle blocking, and consequently requires more vehicle buffering areas. Physical dimensions of a check zone at a node affects vehicle blocking. The larger is a check zone, the more time a vehicle will take to cross it, thereby preventing other vehicles the use of the check zone for a longer time. Aisle space economy has direct influence over the vehicle buffering areas. Vehicle congestion, in general, is inversely proportional to an arc length. The longer is an arc, the lesser will be the need for vehicle buffering zone required at its end. If there is no separate vehicle park where vehicles can be dispatched immediately after unloading a load at a D station, then the vehicles have to temporarily stay put at the D stations in the network. Consequently, vehicle buffering needs at D stations become more critical.

Vehicle dispatching and routeing strategies: Segments (nodes and arcs) of the network are congested in varying proportions depending on which vehicle is assigned which transportation task and which route it follows. Thus, these operational control decisions will directly influence the "loading" of the network.

Vehicle design attributes: Technical design features of a vehicle such as its length and speed also affect the vehicle congestion status of the network. A faster moving vehicle will cross a check zone quickly thereby allowing other vehicles the use of the check zone that much sooner. Physical design of a check zone will depend upon the vehicle length and speed. If the loading/unloading of a vehicle at a P/D station takes an inordinate amount of time, it will tend to block other vehicles waiting to load/unload at the same P/D station.

Future needs: Future material flow requirements, traffic flow intensities in various segments of the network, and possible expansion of the network will also have bearing on vehicle buffering needs.

4.5 Conclusions

The benefits of bidirectional flow AGVSs over unidirectional counterparts are significant in terms of system performances such as throughput rate when the MHS is a critical resource in the shop. For the same number of vehicles, a bidirectional system achieves higher throughput rates than a unidirectional system. When there is a certain fixed production target to be achieved, a bidirectional system may require fewer number of vehicles than a unidirectional system. A prerequisite to realizing and successfully operating a bidirectional AGVS is laying out of vehicle buffering zones in order to manage and control the vehicle blocking and congestion in different segments of the network. Appropriate methods for traffic control and collision avoidance should also be developed. The benefits obtained through improved system throughput rates and smaller AGV fleet sizes generally offset the costs associated with developing and maintaining the control software and managing the system. The benefits of a bidirectional AGVS depend on the characteristics of the specific system under study. A simulation study seems to be an appropriate methodology to estimate the improvements in system performance.

This chapter discusses the issues related to AGVS flow path design. An analytical methodology in the form of a heuristic is presented for the purpose of configuring a given unidirectional flow path design into a hybrid uni/bidirectional one. The heuristic is developed with the aim of reducing material flow distances. Such a reduction is anticipated to result in shorter vehicle journeys and a consequent increase in throughput rate of the system. The heuristic is applied to the hypothetical FMS of Chapter 2 and two alternative hybrid flow designs are obtained. Finally, an all-bidirectional flow design is obtained by converting all paths of the original unidirectional flow network into bidirectional ones.

Simulation has been used as the design validation methodology. The four alternative flow designs are simulated with the following objectives.

1. To make a comparative evaluation of throughput potentials of the test facility when it is operated on any one of the four flow modes.

2. To observe the distribution of vehicle activity time, specially the blocking time,

under the four flow scenarios.

3. To determine location and holding capacity of vehicle sidings in the network.

The results of the simulation study show that throughput potential of the system increases as the amount of bidirectionality in the network is increased. By designing the paths as bidirectional, a higher throughput is achieved and fewer vehicles are required. On the other hand, likelihood of vehicle interference and conflicts increases. Resolution of such vehicle blocking phenomenon requires provision of vehicle buffering areas. As the amount of bidirectionality in the network increases, the location and holding capacity of such areas also increase.

Chapter 5

Vehicle Dispatching Strategies

5.1 Introduction

Material handling is one of the essential components in an FMS. Several authors have stressed that efficient scheduling of the MHS is critical to the overall system efficiency (Raman *et al* 1986, Han and McGinnis 1989). The ability of an AGV based MHS to operate in accordance with its promised potential is dependent upon the operational control measures in force. An AGVS, though more flexible and capable than a non-computer controlled MHS, poses more serious and challenging operational control problems that increase with the level of system automation. The manner by which these problems are resolved determines the operating effectiveness of the total system. One such operational control decision issue is concerned with vehicle dispatching strategies. In a job-shop environment where there is no recognized flow pattern of unit loads, vehicles in an AGVS can be dispersed throughout the network or concentrated in a region at any particular time. Vehicle distribution in the network is an operational control problem. The selected control measures by which vehicles are assigned tasks can affect material flow, buffer storage requirement, machine utilization, and vehicle effectiveness.

A literature survey of vehicle task assignment strategies in an AGVS indicates the pattern on which this field has been explored by researchers. The domain of vehicle dispatching rules can be broadly classified as consisting of two categories —

non-dedicated, and *dedicated* rules (Figure 5.1). The non-dedicated class of vehicle dispatching rules consists of those rules which allow vehicles to visit any load P/D station from any other location. The vehicles are not restricted to move on some specific routes, nor are they dedicated to serve some subset of processing centres. The vehicles operate in what is referred to as a "taxi" system. The vehicle dispatching scheme is considered dynamic and flexible since vehicles can be routed to different locations using different paths. The scheme is more applicable to job-shop type environments where demands over time for a vehicle vary location-wise throughout the facility. This class of vehicle dispatching rules falls further into two categories. The first category of rules is a decision involving the selection of a processing centre from a set of centres simultaneously requesting the service of a vehicle, a decision which usually involves a single vehicle and multiple processing centres. The decision is to prioritize the centres and to dispatch the vehicle to the centre with the highest priority. Egbelu and Tanchoco (1984) referred to this class of decision rules as *vehicle initiated task assignment (dispatching)* rules. The control logic has been referred to by Newton (1985) as *vehicle looks for work*, and by Vosniakos and Mamalis (1990) as *redundant work dispatching*. This sub-category of vehicle dispatching rules can be further classified as consisting of *source driven (push type)* rules, and *demand driven (pull type)* rules. The second category of non-dedicated vehicle dispatching decisions involves the selection of a vehicle from a set of idle vehicles to be assigned to a unit load pickup task generated at some part of the facility. This class of decisions involves a single processing centre and multiple vehicles. Egbelu and Tanchoco (1984) referred to this category of decision rules as *centre initiated task assignment (dispatching)* rules, while Vosniakos and Mamalis (1990) referred to this control logic as *redundant vehicle dispatching*. A pair of rules from each of the two categories of non-dedicated rules is required to accomplish the vehicle dispatching requirements of an AGV based MHS in a job-shop environment.

The dedicated class of vehicle dispatching rules deals with pre-programming the vehicles to follow a fixed sequence of some or all of the load P/D stations. Thus, the vehicles dedicately follow the principle of "merry-go-round". Though the shop production rate may possibly be adversely affected by these rules, but

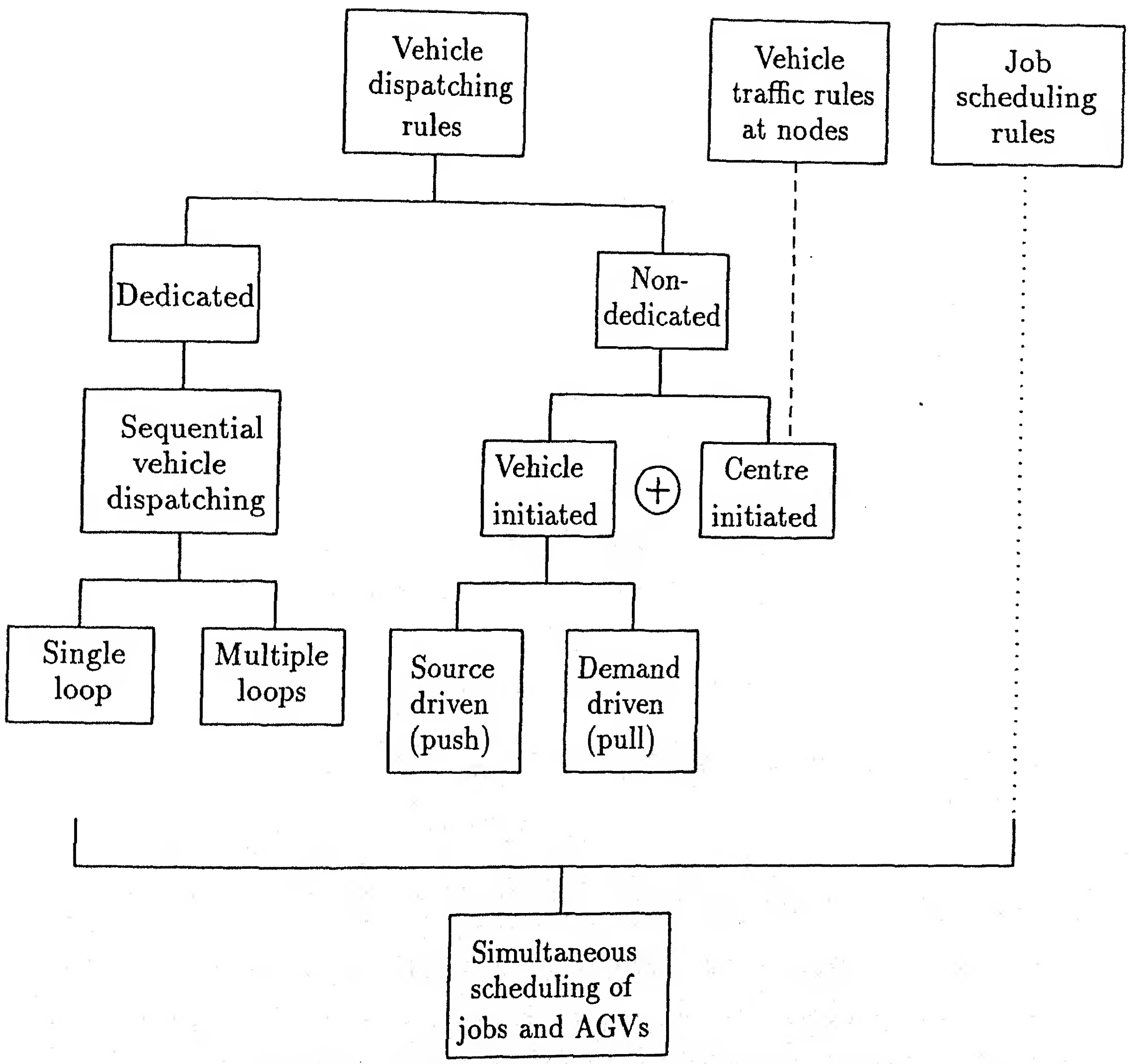

Figure 5.1: Classification and domain of vehicle dispatching rules

there are advantages to be obtained in terms of possible elimination of shop locking phenomenon, and simplicity in traffic control management.

This chapter focuses on vehicle dispatching strategies applicable in a job-shop environment. Various rules from the domain of vehicles dispatching rules are discussed. The likely effects of these rules on the performance of the job shop are postulated. The applicable rules in source driven (push-type), demand driven (pull-type), and centre initiated vehicle dispatching scenarios are first discussed. The dynamic behaviour of an AGVS in an FMS is then highlighted with an emphasis on shop locking phenomenon which may typically be exhibited in an automated job-shop manufacturing environment. The dedicated class of vehicle dispatching rules and simultaneous scheduling of jobs and vehicles are then discussed. The scope of the present work is a simulation study of the test facility. The aim is to make a comparative performance evaluation of various source driven (push-type) and demand driven (pull-type) vehicle dispatching rules. Two criteria have been used for comparison purpose, viz., system throughput rate, and average queue length of unit loads at the input/output buffers of centres. The problem environment, the experimental conditions, and the results of the simulation study are then finally presented.

5.2 Source driven (push-type) vehicle initiated task assignment rules

On the completion of a load delivery task, a vehicle is reassigned to another mission immediately if there is an unattended handling task in the facility. If multiple unit loads are awaiting pickup simultaneously at different locations in the facility, then the vehicle task assignment involves matching the vehicle to the task. It is the event of a vehicle attaining an idle status that invokes the vehicle dispatching mechanism. From an operational point of view the most desirable level of handling effectiveness is that which ensures that unit loads completed at a processing centre are removed promptly and transported to their subsequent destinations with minimum delays. The time-independent AGVS characterization model of Maxwell and Muckstadt

(1982) assumed a steady paced assembly environment. The model assigned vehicle trips to routes, through a heuristic rule, so that the time between visits for pickup/delivery activity at each P/D station was spread uniformly. However, actual operating conditions deviate from this scenario. The degree of deviation is a function of vehicle availability, shop loading, and the AGVS flow path layout. Operating conditions do arise when requests for vehicles from processing centres cannot be immediately satisfied. This is the case when all vehicles are engaged in missions. Such unsatisfied requests are therefore logged and considered for satisfaction when a vehicle becomes idle and available.

Analytical modelling of vehicle dispatching rules has been less frequently attempted by researchers because the problem is NP-complete. Hodgson *et al* (1987) modelled AGVS as a semi-Markov decision process (renewal approach) to study the effects of alternate vehicle dispatching rules and guide path layouts. Generalized control rules for scheduling vehicles were extracted from the (Markov) optimal control policies. The model characterized the relationship between the guide path layout and dispatching rule, and the results appeared consistent with a follow-up simulation study. Many researchers have adopted the methodology of computer simulation to investigate the effect of vehicle dispatching rules on system performance. The scope of these studies encompasses various manufacturing scenarios. The principal contributors have been Egbelu and Tanchoco (1984), Russell and Tanchoco (1984), Ashayeri *et al* (1985), Newton (1985), Cheng (1987), Hodgson *et al* (1987), and Vosniakos and Mamalis (1990).

The procedures by which the processing centres are dynamically prioritized for service by a released vehicle are presented below in the form of heuristic rules.

5.2.1 Distance/time based rules

Nearest Work centre (NW): The basis of this rule is to minimize the percentage of time vehicles travel empty. The decision is to dispatch the released vehicle to the centre whose load P station is closest to the vehicle. Closeness is measured in terms of travel time or distance along the shortest path and in the direction of traffic flow. Despite its obvious advantages the rule is very sensitive to the

location of load P/D stations in the facility. If a load P station of some centre happens not to be the nearest to any vehicle release point (load D station), then according to this rule such a centre may never qualify to receive a vehicle dispatch.

Farthest Work centre (FW): As an antithetical rule to NW, this rule assigns the highest priority to the processing centre that is farthest away from the vehicle. Other than system experimentation, there is no attractive quality to this rule, except for the fact that it may, unintentionally, help diffuse vehicle congestion status by diverting vehicles to less congested areas of the AGVS network.

5.2.2 Buffer based rules

Maximum Output Queue Size (MOQS): Suppose oq_k denotes the number of unit loads in the output queue of processing centre k awaiting pickup and uoq_k is the number of unit loads in the same queue not yet assigned to any vehicle, where $0 \leq uoq_k \leq oq_k$. The decision is to dispatch the vehicle to processing centre j such that

$$oq_j = \max(oq_k), \quad \forall k, uoq_k \geq 1.$$

Maximum Queue Size (MQS): This rule is similar to MOQS rule, except that the consideration of queue size includes both the input and output queues. The rule selects the centre with the largest overall queue level. It is more meaningful when both incoming and outgoing loads share the same queue.

Maximum Unassigned Output Queue Size (MUOQS): The decision is to dispatch the vehicle to processing centre j such that

$$uoq_j = \max(uoq_k), \quad \forall k, uoq_k \geq 1.$$

The difference between MOQS and MUOQS rules is that MOQS rule awards highest priority to a centre which has maximum output queue length provided there is at least one unassigned unit load therein. MUOQS rule, on the other

hand, qualifies further the criterion used above by giving top priority to a centre which has maximum unassigned output queue length.

minimum Remaining Output Queue Space (mROQS): Dispatching decision under mROQS rule is based on output queue capacity and length at each processing centre. If OQ_k represents the capacity of output queue at centre k, then the decision is to dispatch the available vehicle to centre j such that

$$(OQ_j - oq_j) = \min(OQ_k - oq_k), \quad \forall k, uoq_k \geq 1.$$

This rule attempts to prevent machine blocking at centres.

5.2.3 Job attribute based rules

Many of the conventional job scheduling rules can also be applied when a unit load rather than a centre is the focus of assignment of the transportation task to the available vehicle. There is a wide base of literature available on these rules. In fact, Panwalkar and Iskander (1977) report more than 100 such rules. Some of the rules applicable in an AGVS are the following.

First Come First Serve (FCFS): The rule attempts to assign vehicles to centres sequentially in chronological order as requests for empty vehicles are received from the centres. When a centre places a call (request) for an empty vehicle and the call cannot be immediately satisfied, the time the call was generated is saved. The saved call and time are used for future vehicle assignment decisions. When a vehicle becomes available, it is assigned to the centre that has the earliest outstanding saved call and time. The rule is reported to work well when there is sufficient queue capacity, and/or the vehicle speed is very high.

Modified First Come First Serve (MFCFS): This rule is a modification of the FCFS rule. An unsatisfied call for an empty vehicle by a centre and its time are logged as in FCFS rule. However, if subsequent calls emanate from a centre before an earlier saved call from that centre is satisfied, the times of these subsequent calls are not saved. In other words, no centre can have two or more outstanding saved calls simultaneously. At the moment a saved call

from a centre is satisfied, the vehicle need of such a centre is evaluated and updated. If there is still one or more unassigned unit loads in the output queue of the centre, a new call is saved immediately against the centre at the current time.

The above two rules ensure that the elapsed time between the placing of a vehicle request by a centre and the satisfaction of that request is reduced. The number of assignments made to a centre is related to job traffic intensity in that centre. As compared to FCFS, the MFCFS rule prevents a centre with high throughput rate from using most of the time of the vehicles.

Earliest Job Arrival Time (EJAT): The rule is useful if the design objective is to reduce the time jobs spend in the shop. It accelerates jobs through a shop in their order of entry into the shop.

Latest Job Arrival Time (LJAT): The rule is antithetical to EJAT rule. The available vehicle is assigned to pickup a unit load which has spent minimum time in the system.

Shortest Processing Time (SPT): The available vehicle is dispatched to pickup a unit load which has the minimum processing time for the next operation.

Maximum Processing Time (MPT): The rule is antithetical to the SPT rule.

minimum Ratio of Time Spent to System Time (mRTSST): The decision is to assign vehicle to pickup a unit load which has spent minimum time in the system relative to its theoretical system time (processing time plus AGV handling time). The rule is an extension of LJAT rule.

Least Work Remaining (LWR): The available vehicle is dispatched to pickup a unit load which has least amount of work remaining. When the amount of work remaining is computed in terms of number of operations, the rule becomes **Fewest Operations Remaining (FOR)** rule.

Maximum Work Remaining (MWR): The rule is antithetical to the LWR rule. When the amount of work remaining is computed in terms of number of

operations, the rule becomes **Maximum Operations Remaining (MOR)** rule.

Least Expected Waiting Time (LEWT): The decision is to dispatch the available vehicle to pickup a load which has the least expected waiting time at the next centre. Computation of the expected waiting time at the next centre takes into account the vehicle travel time, and operation times of parts having higher priority of being processed than this part at the next centre's input queue. The objective is to find a part which has the highest chance of being processed earliest at the next centre.

5.2.4 Randomized rule

Under this rule a list of all processing centres requesting the service of a vehicle is obtained. From this list a centre is randomly selected (RW) and the released vehicle is dispatched there. The rule, when implemented, can produce results as good as or as bad as any other rule since randomization process encompasses all other rules.

5.3 Demand driven (pull-type) vehicle initiated task assignment rules

The vehicle dispatching rules presented above are based on the attributes of the processing centres from where the loads originate. These rules can therefore be described as source driven vehicle dispatching rules. In none of these rules is the load pickup priority determined based on the states of the load destinations. Therefore, the priority assignment algorithms used by source driven rules are inflexible for application in some manufacturing systems, specially those based on the just-in-time (JIT) principle. One of the attributes of JIT manufacturing concept is that items in production are pulled through the shop rather than being pushed as it is conventionally practised. In a conventional push system, part supply to a processing centre is governed principally by production capacity of its predecessors. Under the pull concept of JIT system, the supply of parts to a centre is timed and controlled

by the demand of the centre. What is required for JIT manufacturing therefore is a demand driven rule.

An AGV, after transferring its load at a D station, is released from its current assignment. It is at the D stations that it gets its new assignments. In a conventional AGVS, it receives its next call from any one of the P stations to transfer load to the corresponding D station, whether that D station has a requirement of material or not. This is a push strategy. The parts are conveyed regardless of the status of the load destinations. In an AGVS tailored for JIT philosophy, the AGV receives its next assignment call from one of the D stations which has a requirement for material from its corresponding P station. Thus, material is pulled rather than pushed. The pull strategy imposes strict requirements on inventory levels and supply demand protocols which render conventional AGV delivery strategies ineffective and counter-productive.

To make JIT functional, it is vitally important that appropriate vehicle dispatching rules based on the concept of part pulling be developed. The modelling of JIT systems should include such pulling mechanisms. In assigning vehicles to available handling tasks, priority should be given to the supply of parts to processing centre currently indicating the greatest demand for new supplies. What is required, therefore, is a demand driven rule rather than a supply driven rule. Under the demand driven rule, it is the states of load destinations or load demand stations that constitute the basis for allocating empty vehicles. On the other hand, in source driven rules, it is the states of the load sources that are the basis for allocating empty vehicles.

Egbelu (1987b) was the first to acknowledge the distinction in AGVS operational requirements between push and pull systems. He developed a demand driven vehicle dispatching heuristic by assigning a threshold value for input queue at each centre. The threshold value, a certain number less than the input queue capacity, was a mechanism for implementing a pull effect by controlling the maximum number of parts that could flow between centres. The rule placed high priority on centres with idle machines, machine blockages, empty input queues, and lowest ratio of completion, in that order (a hierarchical heuristic). When no pending demand

existed, the rule reverted to a source driven rule in order to avoid vehicle idleness, and to prepare for unanticipated surges in vehicle demands at a future time.

Occena and Yokota (1991) introduced threshold values on the output queues also at each centre to control material flow between various centres as well as within each centre. They described a maximum demand vehicle dispatching rule that was sensitive to different degrees of demand. A more severe demand, as a result of machine starvation, occurred when output queue count of a centre fell below its threshold value and yet its input queue was empty. A less severe demand occurred when input queue count fell below its threshold value. Higher priority was given to a centre with more severe demand. Unlike Egbelu's dispatching rule, no source driven rules were to be applied, even in the case of no pending demands.

A drawback of the two above mentioned works is the introduction of a new set of decision parameters, viz., threshold values on input and/or output queues. This widens the scope of system experimentation.

Yim and Linn (1993) conducted a Petri net based simulation study of an FMS to investigate the effect of different push/pull rules on the FMS performance.

Some of the demand driven vehicle dispatching rules are described below.

Nearest Destination (ND): This is a new dispatching rule which has been formulated here and tested in the simulation experiment described later in this chapter. The decision is to assign the released vehicle that load transportation task which would take minimum distance/time to accomplish. The total distance/time of the transportation task is calculated from the vehicle's current location to the P station of a source centre, and from there to the D station of a destination centre. The basis of this rule is to minimize the total journey time of the vehicle which includes both the loaded and empty travels.

Farthest Destination (FD): This rule is antithetical to the ND rule and selects that pair of source and destination centres which would result in maximum journey time for the released vehicle.

Earliest Inter-Arrival Time (EIAT): The decision is to deliver a unit load to a centre that has experienced the longest time gap since the last load arrived.

This rule corresponds to the FCFS source driven rule.

minimum Input Queue Size (mIQS): That centre is selected for load delivery which has minimum input queue size. The rule corresponds to the MOQS source driven rule.

Maximum Remaining Input Queue Space (MRIQS): The decision is to deliver a unit load to centre with maximum queue space remaining in its input buffer. The rule corresponds to the mROQS source driven rule.

5.4 Centre initiated task assignment rules

When multiple vehicles are idle (unassigned) simultaneously and a pickup task arises, appropriate criteria must be established for selecting an idle vehicle to assign the task (matching task to vehicle). The vehicle with the highest priority is dispatched to respond to the request. Several heuristic rules can be employed for assigning priorities to vehicles for dispatching. Some of these are described below.

5.4.1 Distance/time based rules

Nearest Vehicle (NV): Under this rule the pickup task is assigned to an available vehicle which is nearest to the load P station from where the call has emanated. The nearness can be measured in terms of either shortest travel distance or shortest travel time. For a congested traffic network, the shortest travel distance path may not necessarily be the shortest travel time path (see Chapter 6).

Farthest Vehicle (FV): This is an antithetical rule to the NV rule. It does not provide any direct usefulness as a viable dispatching rule, but it does show the system designer what effect unnecessary empty vehicle travel could have on system handling effectiveness. However, the rule may prove to be a boon by occasionally producing unexpected effect of avoiding vehicle interference by dispatching the farthest away vehicles to load P stations.

5.4.2 Vehicle attribute based rules

Longest Idle Vehicle (LIV): The rule assigns the highest dispatching priority to the vehicle that has remained idle for the longest time among all the idle vehicles.

Least Utilized Vehicle (LUV): The decision is to dispatch that vehicle which has had minimum utilization, or in other words, the longest cumulative idle time among all the idle vehicles.

The advantage of these two rules is their workload balancing effect on all participating vehicles.

5.4.3 Randomized rule

Under this rule, the pickup task is randomly assigned to any available vehicle (RV) in the shop without regard to its relative location or its utilization.

5.5 Shop locking phenomenon

A shop is considered locked if any one or both of the following two conditions exist — centre blocking, and vehicle fleet blocking. These conditions are described in the subsequent subsections.

5.5.1 Centre blocking

A centre is declared blocked when none of its running machines is in a position to download its current load onto the output queue because the queue itself is full. Empty vehicles to free some spaces from the output queue are either not available or the ones which have been dispatched for load pickup from the output queue cannot get to their destination due to interference from other vehicles. The immediate effect is starvation of next centres in routeing sequences of part types present in output queue of the centre, and reduction in system efficiency. As new deliveries continue to take place into the centre, the input queue too grows to its full capacity resulting into

all machines of the centre becoming blocked. The centre, thus, becomes a bottleneck resource in the system, setting up a chain reaction which gradually propagates to other centres in the shop causing a complete seizure of material flow.

The main causes of centre blocking phenomenon are limited local buffer capacities at the centres, improper location of load P stations relative to the D stations in the AGVS flow path, and adoption of injudicious vehicle dispatching and routeing rules. The vehicle dispatching rules may bias some centres in the wrong order. Thus, some centres almost never satisfy the dispatching criteria. This may happen, for instance, when load P stations in the system are not well located relatively to the D stations and rules such as NW/FW, NV/FV, which are derivatives of distance measures, are adopted.

5.5.2 Vehicle fleet blocking

A vehicle is considered blocked when its intended movement is arrested to a standstill status. Whether it is loaded or empty, the vehicle cannot move because either the check zone in question is being occupied by some other vehicle or the next arc in which the vehicle seeks entry is not available to it. The former cause results in temporary blocking of the vehicle since it implicitly assumes that at least one vehicle in the system, the one which is currently crossing the node, is in motion. All the vehicles in the fleet are not blocked from movement. The latter cause is more serious. A vehicle operating in a bidirectional AGVS flow path network may find its intended entry into the next arc interfered by other vehicles because these vehicles are forcing a reverse direction of traffic flow in that arc (upstream blocking). The vehicle may itself interfere this way with movements of other vehicles. When its movement is thus blocked, the effect tends to be rather of permanent nature. Soon all the other vehicles distributed in the network also find their movements impeded. None of the loaded vehicles transporting unit loads can make its delivery, nor any empty vehicle dispatched for load pickup can get to its destination. This aspect of shop locking phenomenon is manifested in a bidirectional flow path when adequate vehicle buffering zones have not been provided or when efficient and intelligent methods for diverting blocked vehicles to other less congested arcs have not been

deployed. Gridlock occurs when a series of vehicles want to move on track sections that are currently occupied by other vehicles in a chain of vehicles that forms a closed-loop.

5.5.3 Remedial measures for preventing shop locking

Remedial measures to prevent occurrence of shop locking include the following.

Provision of central buffer area: This scheme requires diverting loaded and blocked vehicles to a central buffer area to have their loads delivered there. Thereafter, they are directed to the shop floor to release blocked centres. The vehicles are subsequently returned to pickup the buffered loads for delivering at their appropriate destinations.

Provision of vehicle buffer areas: This scheme is more relevant in the context of a bidirectional flow path layout of an AGVS. It prevents shop locking on account of vehicle fleet blocking.

Vehicle dispatching strategies: Centre blocking can be prevented by making an appropriate selection of a vehicle initiated dispatching rule. Buffer based vehicle initiated dispatching rules such as MOQS, MUOQS, mROQS, etc., have more potential in achieving the desired effect.

Vehicle routeing strategies: Intelligent software control techniques can be devised which would route vehicles dynamically on non-congested routes. Such routes may be distance- or time-wise more longer when compared to the shortest routes. But shortest routes are also generally the busiest and consequently the most blocked routes, specially in a bidirectional flow path network. The dynamic routeing strategy coupled with the intelligence built into the vehicles must be able to recognize traffic congestion status and initiate actions to diffuse it by diverting the vehicles on the routes which are less congested. Further discussion of vehicle routeing strategies has been deferred to the next chapter.

Input/output and flow control measures: These measures are adopted to prevent centre blocking. Input control is exercised by allowing a limited number

of loads circulating at a time in the system. Shantikumar and Stecke (1986) suggested number of pallets available in the system as the upper bound on number of loads in the system. For the flow control, threshold values on input/output queues can be used to expedite/slow down the part entry/exit from a centre (Ro and Kim 1990). For the output control, the part which has completed the last operation has to be awarded the top pickup priority (Shantikumar and Stecke 1986).

5.6 Dedicated vehicle dispatching rules

When a subset of participating vehicles serve a subset of processing centres exclusively, the vehicle dispatching is termed as dedicated. Sequential Vehicle Dispatching (SVD) rule is one such important example of dedicated rules. In this scheme of dispatching, all the available vehicles are pre-programmed to visit the load P/D stations in the same fixed sequence that forms a closed-loop. If a P station has a load when it is visited by a vehicle, the load is picked up and transported to its destination. Otherwise, the vehicle proceeds to the next P station in the sequence. The scheme of vehicle dispatching is static as opposed to a dynamic vehicle dispatching strategy of non-dedicated class of dispatching rules. An inherent quality of this strategy is the elimination of any possibility of shop locking. In a new facility, this requires locating the centres along a loop to minimize vehicle travel time. However, in complex facilities with large number of centres or ones with fixed layouts, the flexibility to locate all P/D stations along a loop is highly constrained. In such cases, a sequence has to be selected through a heuristic procedure or by solving the corresponding travelling salesman problem.

The SVD rule has been studied by many researchers. Egbelu and Tanchoco (1984) first suggested it. Tanchoco and Sinriech (1992), and Sinriech and Tanchoco (1992b, 1993) presented analytical modelling of an Optimal Single Loop (OSL) design which minimizes vehicle travel time (loaded and empty). The vehicle dispatching strategy employed by Ozden (1988) was designed for a system where all centres were interconnected by at least one simple loop. The empty AGV ran along

a simple, unidirectional, fixed-sequence outer loop until it found a unit load waiting to be picked up. The AGV, with a carrying capacity of two unit loads, picked up at least one such unit load and headed for the nearest D station (bidirectional inner aisles). If the AGV had additional free space, it could pick up another unit load en-route and reschedule its route depending upon the nearest destination.

Bartholdi and Platzman (1989) used a similar vehicle dispatching strategy, called First Encountered First Served (FEFS), for AGVs travelling in a single, simple loop under decentralized control. With a load carrying capacity of three units of load, the AGV continually circulated in the loop until it encountered a unit load awaiting pickup. It could pickup other unit loads en-route, if space permitted. Unit loads were delivered whenever their destinations were encountered.

Malmborg (1994) described an analytical method for predicting WIP storage requirements resulting from a fixed number of looping AGVs serving a line layout. The methods was based on a model of storage queue dynamics that predicted material flow rates and vehicle response times resulting from vehicle dispatching within a single loop system.

The tandem configuration of AGVS flow path as proposed by Bozer and Srinivasan (1989, 1991) is an extension of the single loop principle. It consists of multiple non-intersecting simple loops. The SVD rule is also applicable in this circumstance.

5.7 Simultaneous scheduling of jobs and AGVs in an FMS

FMS scheduling refers to a time-phased allocation of all the system resources such as machines, tools, fixtures, AGVs, pallets, etc. From a system perspective, an FMS basically consists of two interrelated subsystems — a machining subsystem and a materials handling subsystem. The two subsystems are so closely integrated that the performance of one affects the other. While each job completion at a processing centre generates an arrival to the AGV subsystem, completion of a transportation service by an AGV determines job potentials for the processing centres. In other words, outputs from one subsystem are the inputs to the other subsystem. In a

typical FMS, the system status changes so frequently that at one time the machining subsystem can be a "constrained resource" or a "drawing force" for the material flow whereas at some other time the AGVS becomes a critical resource and eventually dominates the schedule. Because of this two-way interaction, both subsystems must be taken into account simultaneously in scheduling an FMS. Since the problem of scheduling of the machining subsystem and the AGV subsystem are both NP-complete, heuristics are usually proposed for their solution. These heuristics form a dispatching mechanism consisting of two independent sets of rules, one for each type of resource. Thus, because of their myopic nature, a job having the highest priority on the current centre may wait in the output queue for a long time while a lower priority job in the system is being processed in the next centre. There exists a need to organize this information on hierarchical levels in order to integrate the two scheduling mechanisms.

Wu and Wysk (1989) developed on-line scheduling and control rules for machines and AGVs in FMSs. Jaikumar and Solomon (1990) developed analytical results about the design and operation of certain types of AGVSs and some associated production planning and scheduling problems. They analyzed the assignment of part types to machines, the sequencing of jobs on each machine, the determination of the AGV fleet size, and the scheduling/dispatching of the AGVs. Their primary objective was to maximize machine utilization and minimize the AGV travel time. By developing a hierarchical decision scheme for the analysis of these problems they showed that the special structure exhibited by many systems found in practice could be exploited, and polynomial time algorithms can provide full machine utilization under realistic conditions.

Ro and Kim (1990) conducted a simulation study to test various alternate process plan selection rules in an FMS through simultaneous scheduling of jobs and AGVs. Blazewicz *et al* (1991) integrated the machine and vehicle schedules. For the case of a given machine schedule, they presented a simple polynomial time algorithm that checks the feasibility of a vehicle schedule and constructs it whenever one exists. Then a dynamic programming approach to construct optimal machine and vehicle schedule was proposed. This technique resulted in a pseudopolynomial time

algorithm for a fixed number of machines. Simultaneous scheduling of jobs and AGVs was also studied by by Sabuncuoglu and Hommertzheim (1992a). They proposed an on-line algorithm for the FMS scheduling problem. The algorithm used various priority schemes and relevant information concerning the load of the system and the status of jobs in the scheduling process. This information was organized into hierarchical levels. In a later paper (Sabuncuoglu and Hommertzheim 1992b), they further investigated FMS machines and AGVs simultaneous scheduling rules under a variety of experimental conditions.

Ulusoy and Bilge (1993) developed an iterative scheduling algorithm to solve the machine and vehicle scheduling subproblems. At each iteration, a new machine schedule, generated by a heuristic procedure, was investigated for its feasibility to the vehicle scheduling subproblem which was handled as a sliding time window problem. As opposed to a real-time dispatching scheme, this off-line scheduling procedure first anticipated the complete set of flow requirements for a given machine schedule and then made vehicle assignments accordingly. That is, the assigned AGV could start for the load P station even before the operation on the machine was actually completed.

5.8 Simulation study

Vehicle dispatching function is an important system operational control measure. It affects the selection of various routes taken by empty vehicles when they are heading for load pickup assignments. It thus "loads" different segments (nodes and arcs) of the network to different degrees. Consequently, throughput rate of the system may be influenced. The scope of the present work in this chapter is a simulation study of the all-bidirectional (Bi-III) test facility of Chapter 4 (Figure 4.3). The main aim is to compare the throughput potential of the facility when different dispatching rules (push- and pull-type vehicle initiated, and centre initiated) are invoked. Two experimental conditions are mainly set up in the simulation study in the form of case studies. The first case study involves comparing throughput performance of the system when queues at input/output buffers of the processing centres are assumed

to be capacitated, as previously done in Chapters 3 and 4. In the second case, the exercise is repeated with infinite buffer capacity. With the exception of buffer capacity, the other experimental conditions remain unchanged. These include the following.

1. Mean of the Poisson job arrival process = 200 unit loads per shift.
2. P/H ratio = 3.107.
3. Processing centre data, as given in Table 2.1.
4. Job parameters, as given in Table 2.2.
5. AGVS network = Bi-III (Figure 4.3).
6. Vehicle travel time matrix, as given in Table 4.4.
7. Job scheduling rule = FCFS.
8. Vehicle traffic rule at nodes = FCFS.
9. Static vehicle routeing.

The simulation run length, replications, variance reduction and output analysis techniques, etc., again, remain the same as in the previous two chapters. The two case studies are presented below.

5.8.1 Capacitated buffers

Capacitating the local input/output buffers in front of each processing centre has the detrimental effect of creating shop locking conditions. Since the buffer capacity of a centre is limited, and since the centre may not get timely services of vehicles for load pickup and delivery due to inherent randomness of FMS, the probability of the centre's machines getting blocked or remaining starved increases. The system's operating behaviour, in other words, becomes time-phased and its throughput rate becomes sensitive to vehicle dispatching strategies. It is with this aim that variation

Table 5.1: Throughput variation with push-type vehicle initiated dispatching strategies (capacitated buffers)

No. of AGVs	Average throughput rate					
	NW	FW	MOQS	mROQS	FCFS	MFCFS
8	*	*	*	156.75	*	157.50
9	*	136.25	*	173.75	*	175.25
10	*	153.00	*	189.50	*	187.50
11	181.50	167.75	*	195.25	*	186.50
12	*	181.25	*	193.50	*	191.00
13	*	192.50	*	195.25	*	187.00

	EJAT	SPT	MPT	FOR	MOR
8	154.25	*	*	170.50	*
9	173.50	*	*	184.25	*
10	186.75	143.25	*	*	*
11	189.25	133.75	*	196.25	*
12	192.00	139.25	*	195.00	*
13	194.50	152.50	*	*	*

* Shop locking encountered

in throughput rate on account of vehicle dispatching rules is studied in this chapter. The experiments and their results are discussed below.

Throughput rate v/s push-type vehicle initiated dispatching rules: Several source driven (push-type) rules are tested. These include NW, FW, MOQS, mROQS, FCFS, MFCFS, EJAT, SPT, MPT, FOR, and MOR. Centre initiated dispatching rule which is used in this setup is the NV rule. The results are summarized in Table 5.1.

It is observed from these results that operating behaviour of the system is characterized by shop locking phenomenon under several vehicle dispatching rules, viz., NW, MOQS, FCFS, MPT, and MOR, and for certain fleet sizes under FW, SPT, and FOR rules. Application of the distance based NW rule implies that an idle vehicle is assigned to pickup a load, more often than not, from the same P/D point where it has just then delivered its load. The rule aims at minimizing empty travels of vehicles. It is this rule which forms the basis of analytical model of Maxwell

and the proposed model for estimation of empty vehicle travel time (Chapter 3). However, the rule ignores the urgencies of centres located farther away from the idle vehicle. As a result, some centres may never qualify to receive empty vehicles. The FCFS rule is biased towards centres with high activity levels. Such centres have higher processing rates and subsequently draw more number of empty vehicles than other centres with lower processing rates. This unbalanced workload on centres creates imbalance in distribution of vehicles in the network. The MPT rule tends to load those centres which have low processing rates (high processing times). If the subsequent processing needs of such jobs are smaller, then these jobs may not be picked up at all by empty vehicles. This again creates imbalance in the work flow. The MOR rule favours those centres which lie relatively earlier in the processing sequence of the jobs. As a result, newer jobs are continuously fed into the system, whereas jobs towards completion of their processing requirements may never be picked up. The buffer based MOQS rule also leads to shop locking. From the actual statistics for all these rules, there is a strong indication that locking occurs at very early stages of the experiments, that is, in the second shift.

Excluding the rules and/or fleet sizes which induce shop locking conditions, the remaining results are plotted in Figure 5.2. The figure shows that all the plotted rules are not equally responsive in meeting the throughput target. The distance based FW rule enforces longer empty trips, thereby adversely affecting system throughput rate. The SPT rule, which has been reported to perform very well in many other manufacturing scenarios, does not produce expected results. The throughput levels obtained by this rule are the lowest when compared with other rules. The remaining rules, that is, mROQS, MFCFS, EJAT, and FOR yield throughput rates which are similar to each other, though with minor variations. At the optimal fleet size of 10 vehicles, the results do not vary significantly.

Throughput rate v/s pull-type vehicle initiated dispatching rules:

The demand driven (pull-type) rules which are tested in this experiment include ND, FD, EIAT, mIQS, and MRIQS rules. The simulation results are summarized in Table 5.2 and plotted in Figure 5.3.

The figure shows that the pull-type rules yield throughput results which have

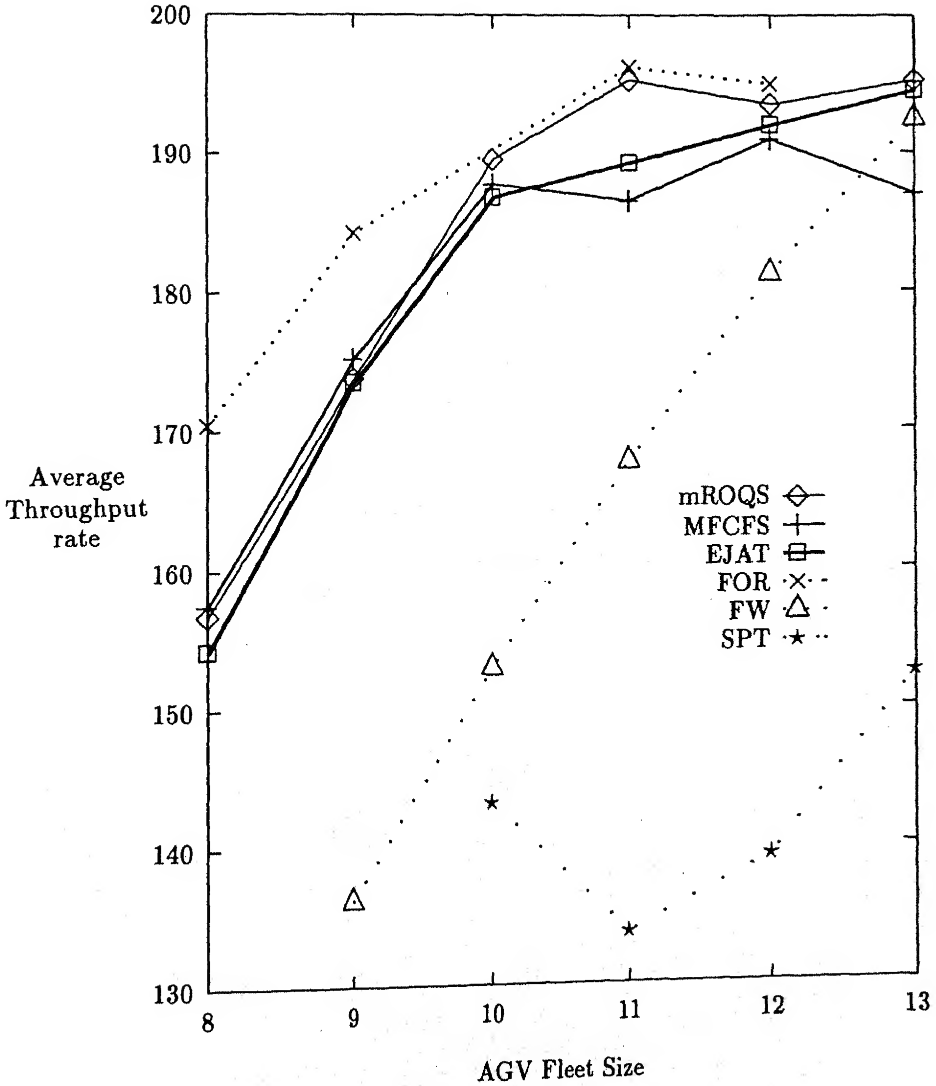

Figure 5.2: Throughput variation with push-type vehicle initiated dispatching strategies (capacitated buffers)

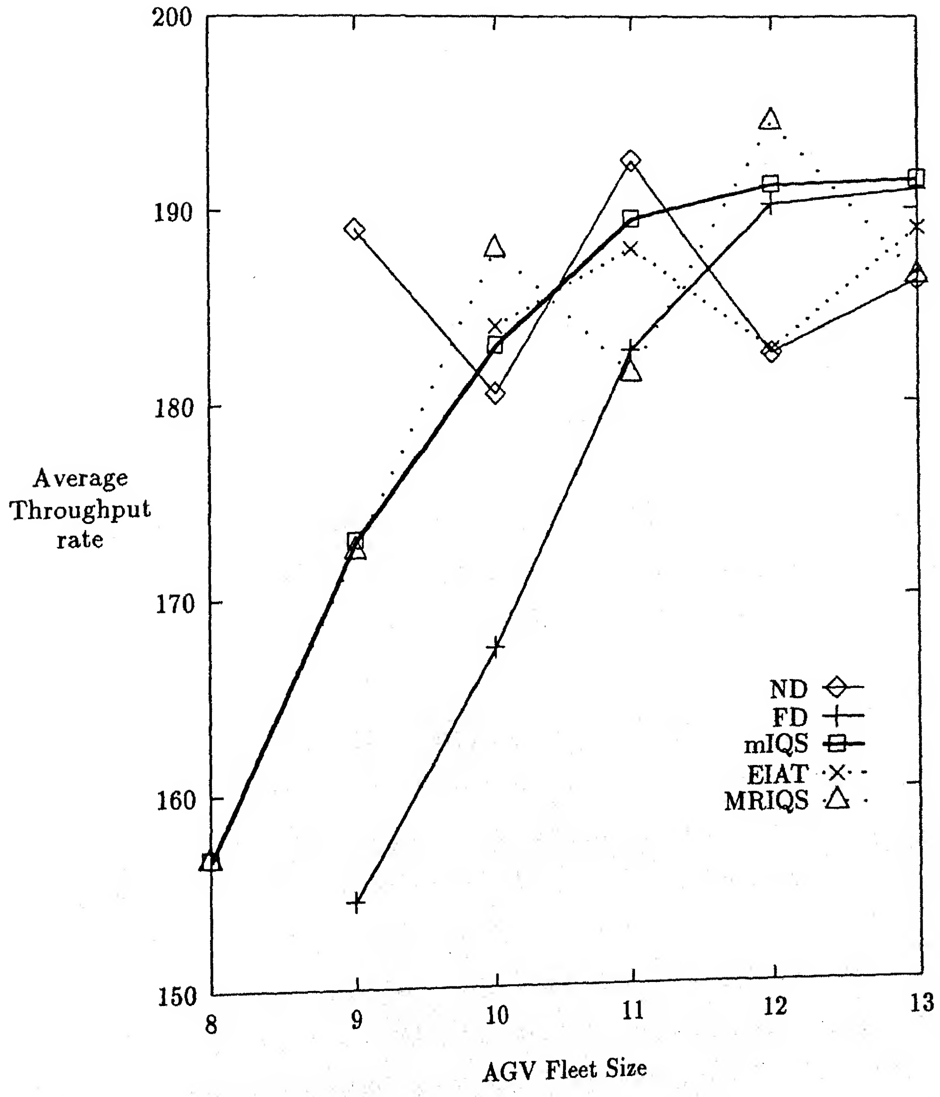

Figure 5.3: Throughput variation with pull-type vehicle initiated dispatching strategies (capacitated buffers)

Table 5.2: Throughput variation with pull-type vehicle initiated dispatching strategies (capacitated buffers)

No. of	Average throughput rate				
AGVs	ND	FD	EIAT	mIQS	MRIQS
8	*	*	*	156.75	156.75
9	189.00	154.50	*	173.00	172.50
10	180.50	167.50	184.00	183.00	188.00
11	192.50	182.75	188.00	189.50	181.50
12	182.50	190.25	182.75	191.25	194.50
13	186.25	191.00	189.00	191.50	186.50

* Shop locking encountered

higher variability than those obtained through push-type rules. The distance based FD rule decidedly produces inferior results on account of higher empty travels enforced on the vehicles. The mIQS rule yields steadily increasing pattern of throughput results and is comparable to the mROQS, MFCFS, EJAT, and FOR push-type rules. The remaining pull-type rules, that is, ND, EIAT, and MRIQS exhibit an erratic behaviour which does not seem to stabilize even at higher fleet sizes. Shop locking is encountered for certain fleet sizes for ND, FD, and, EIAT rules.

Throughput rate v/s centre initiated dispatching rules:

The centre initiated dispatching rules which are tested in this experiment include NV, FV, LIV, and LUV rules. The vehicle initiated rule which is used in combination with these rules is the push-type EJAT rule. The simulation results are summarized in Table 5.3 and plotted in Figure 5.4.

It is to be observed from the results that shop throughput rate as a measure of shop performance does not differ significantly according to centre initiated dispatching rules. This observation is in conformity with that of Egbelu and Tanchoco (1984) who argued that when there is a large volume of material flow in a system, the vehicles in the AGV fleet are rarely free to allow invoking of a centre initiated rule for dispatching the vehicles. Instead, dispatching is governed completely by vehicle initiated rules. The relative importance of the two dispatching mechanisms

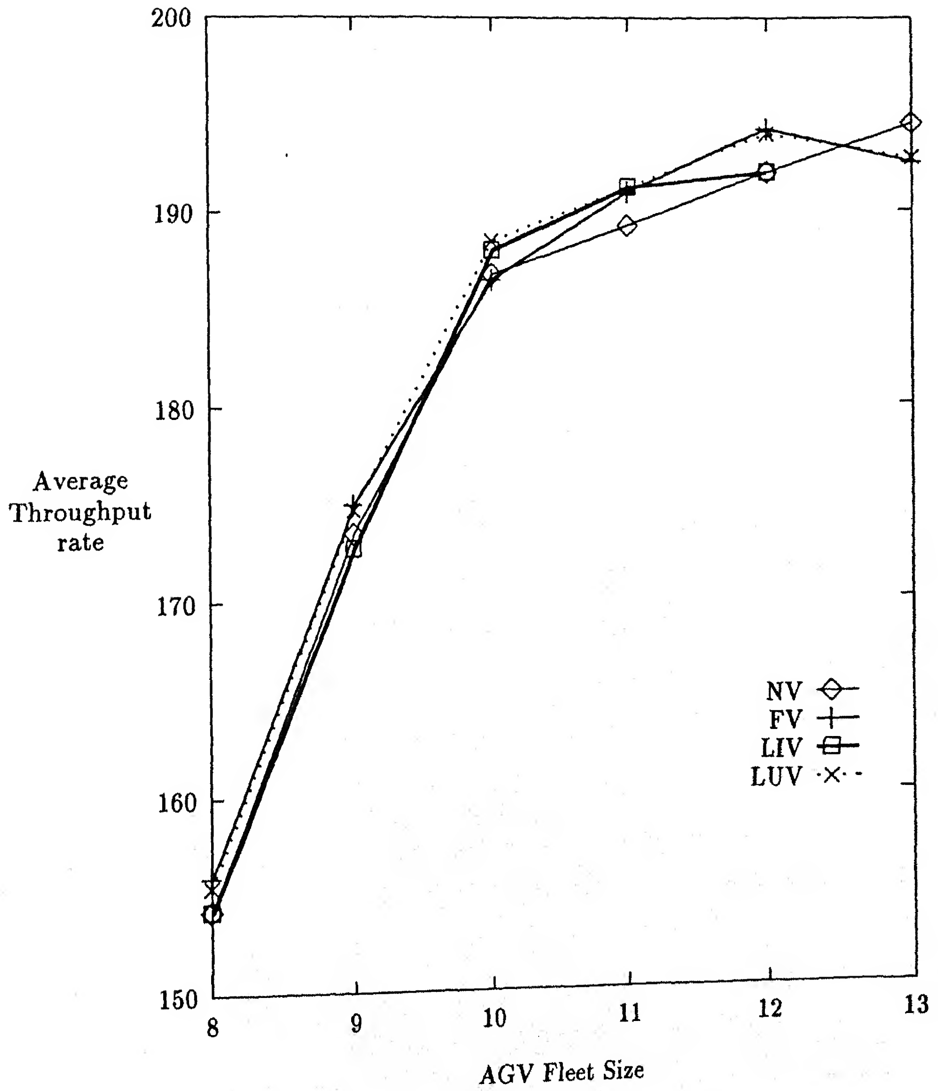

Figure 5.4: Throughput variation with centre initiated dispatching strategies (capacitated buffers)

Table 5.3: Throughput variation with centre initiated dispatching strategies (capacitated buffers)

No. of	Average throughput rate			
AGVs	NV	FV	LIV	LUV
8	154.25	156.00	154.25	155.50
9	173.50	175.00	172.75	174.75
10	189.75	186.50	188.00	188.50
11	189.25	191.00	191.25	*
12	192.00	194.25	192.00	194.00
13	194.50	192.50	*	192.75

* Shop locking encountered

is further indicated by the vehicle dispatching ratio curve for Bi-III flow path design in Figure 4.6.

5.8.2 Uncapacitated buffers

Operating rules notwithstanding, the blocking of processing centres is the direct result of capacitated queues. By relaxing the queue capacity constraint, the locking effect can be eliminated. This provides the opportunity to assess the actual buffer space requirements under unconstrained conditions. To explore this postulate, the facility is simulated under the unconstrained (infinite) queue capacity. The simulation experiments and their results are described below.

Throughput rate v/s push-type vehicle initiated dispatching rules:
The source driven (push-type) rules which are tested in this experiment include NW, FW, MOQS, mROQS, FCFS, MFCFS, SPT, MPT, and FOR rules. And NV rule is the centre initiated rule which has been combined with these rules. MOQS, and mROQS rules yield the same throughput since at infinite queue condition they collapse to the same rule. The simulation results are shown in Table 5.4 and plotted in Figure 5.5.

Looking at the results, it is observed that the NW rule yields much higher throughput rate at smaller fleet sizes as compared to all other rules. Since the rule aims at minimizing empty trips of the vehicles, and since the buffer capacity is not

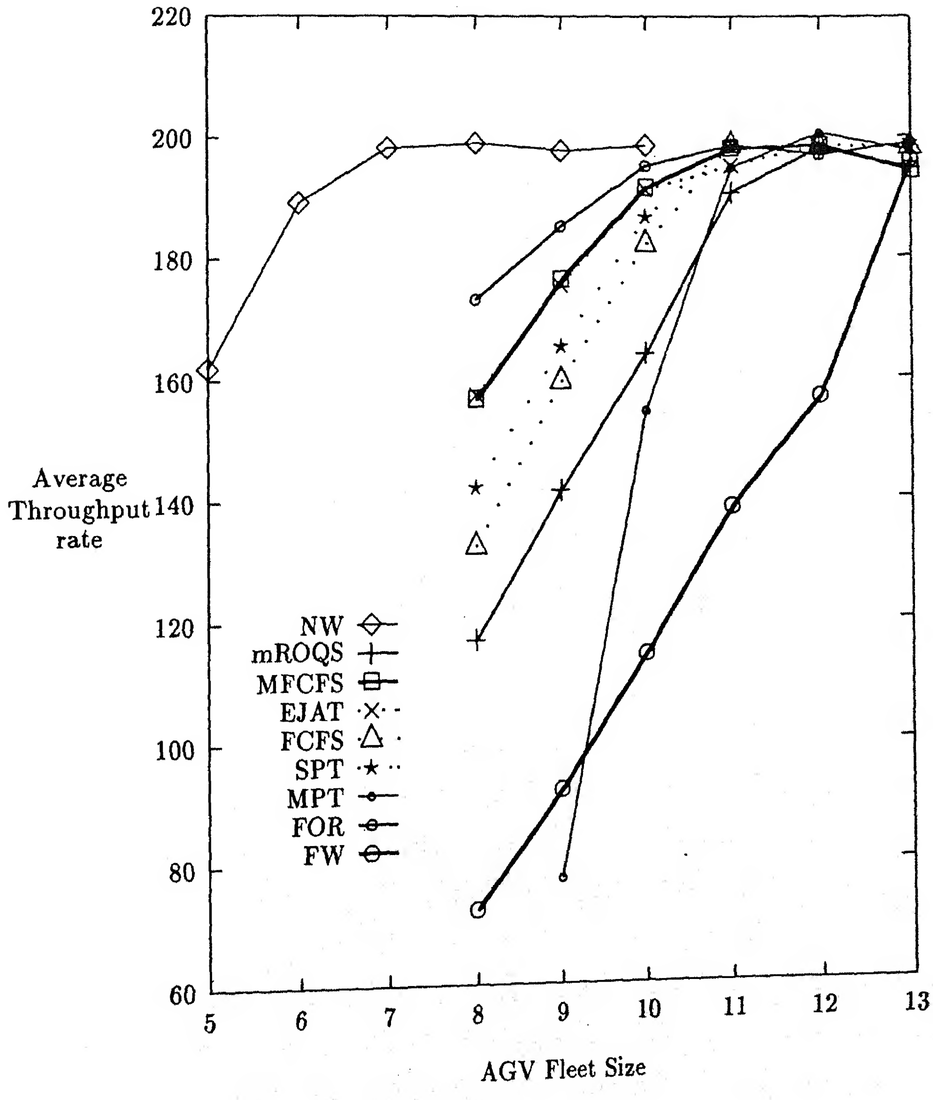

Figure 5.5: Throughput variation with push-type vehicle initiated dispatching strategies (uncapacitated buffers)

Table 5.4: Throughput variation with push-type vehicle initiated dispatching strategies (uncapacitated buffers)

No. of AGVs	Average throughput rate NW	FW	mROQS	FCFS	MFCFS
5	162.00				
6	189.25				
7	198.25				
8	199.00	72.50	117.00	132.50	156.75
9	197.75	92.25	141.75	159.75	176.50
10	198.50	114.50	164.25	182.25	191.50
11		138.75	190.75	198.50	198.00
12		157.00	198.00	198.25	198.50
13		196.25	194.75	198.25	194.25
	EJAT	SPT	MPT	FOR	
8	157.50	142.25		173.25	
9	175.50	165.50	77.50	185.25	
10	191.25	186.75	154.75	195.25	
11	195.25	198.50	194.75	198.50	
12	198.50	198.25	200.50	197.00	
13	198.25	199.00	197.50	199.00	

constrained at any centre, the idle vehicles have greater likelihood of finding loads ready to be picked up from the same locations where they have made deliveries. As a result, the empty travel time is considerably reduced and consequently, the throughput rate increases. It is further observed that the analytical model proposed by Maxwell starts with the objective of minimizing empty travels and presumes that buffer capacity is not a constraint. It estimates the number of vehicles required as 6 (Table 4.5), a fleet size which is validated by the simulation results. However, the rule is reported to yield large queue lengths at input/output buffers at the centres (Egbelu and Tanchoco 1984). As far as other rules are concerned, the FW rule performs poorly on account of longer empty trips enforced on the vehicles. The MPT and the MOQS/mROQS rules yield 95% of throughput target at a fleet size of 11 vehicles, 1 more than what is required by other rules. The remaining rules, that is, FOR, MFCFS, EJAT, SPT, and FCFS yield maximum throughput rate at

Table 5.5: Throughput variation with pull-type vehicle initiated dispatching strategies (uncapacitated buffers)

No. of	Average throughput rate				
AGVs	ND	FD	EIAT	mIQS	MRIQS
5	95.50				
6	126.25				
7	152.00				
8	188.50	64.00	10.25	155.50	148.00
9	197.25	80.00	73.25	173.75	157.25
10	196.75	84.75	143.75	189.00	187.00
11		99.25	196.00	195.50	199.50
12		152.50	197.50	199.75	195.75
13		197.00	198.25	198.25	197.50

a fleet size of 10 vehicles. They, however, differ within themselves in throughput rates at smaller fleet sizes.

Throughput rate v/s pull-type vehicle initiated dispatching rules:

The above experiment is repeated with the following demand driven (pull-type) rules — ND, FD, EIAT, mIQS, and MRIQS. The simulation results are summarized in Table 5.5 and plotted in Figure 5.6.

Looking at the results, it is observed that ND and FD rules yield similar throughput rates as NW and FW push-type rules. The ND rule yields much higher throughput rates at smaller fleet sizes as compared to other rules. On the other hand, the FD rule yields inferior results. The EIAT rule has a very poor throughput response at lower fleet sizes. It achieves the throughput target at 11 vehicles, 1 more than what is required by mIQS and MRIQS rules. The latter two rules yield results which are similar to each other.

The above two experiments are conducted for throughput rate as the system performance measure. Another measure of performance on which the various vehicle dispatching rules (both push- and pull-types) can be compared is the average queue length of unit loads at input/output buffers at each centre. When buffers are assumed to be uncapacitated, the average queue length is a good measure to help in assessment of actual buffer space requirements. The following two experiments

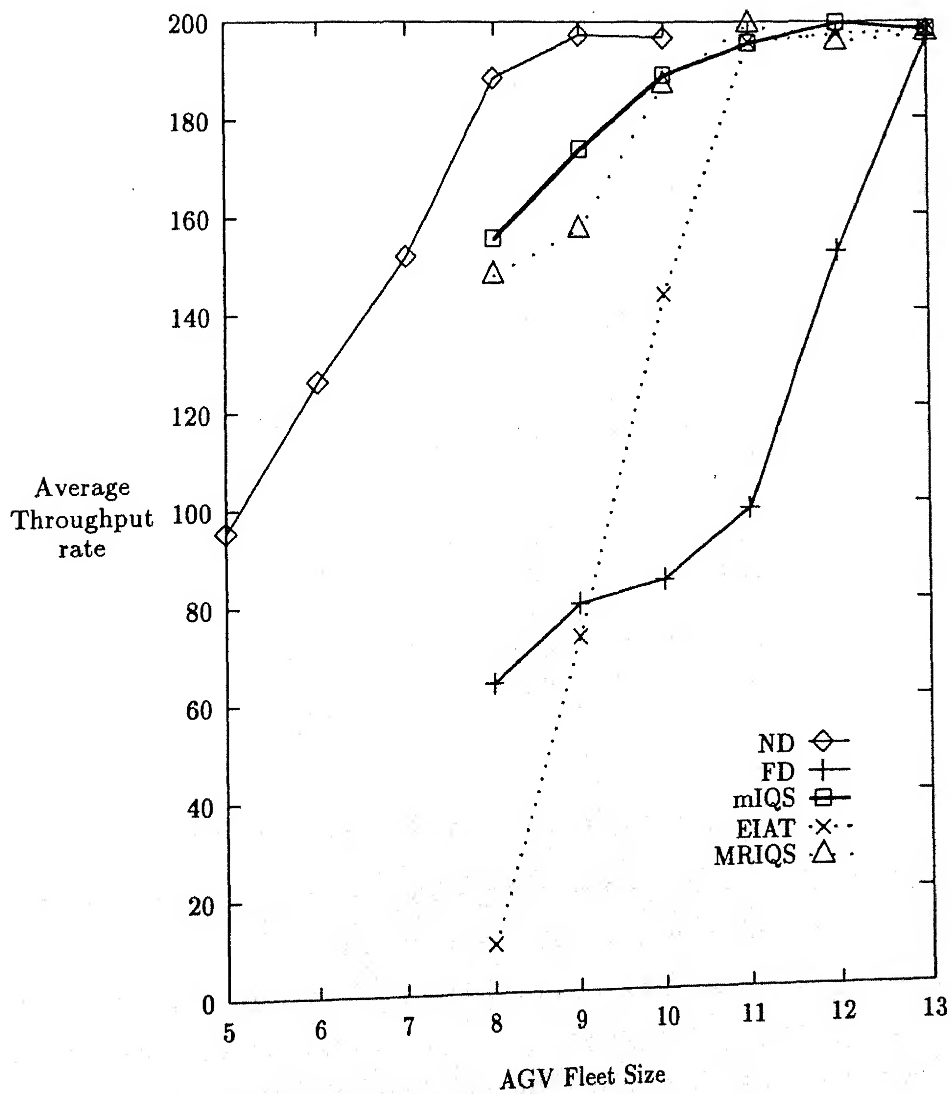

Figure 5.6: Throughput variation with pull-type vehicle initiated dispatching strategies (uncapacitated buffers)

Table 5.6: Average input queue length variation with push-type vehicle initiated dispatching strategies

Centre	Average input queue length			
no.	FCFS	MFCFS	SPT	FOR
1	0	0	0	0
2	11.87	11.27	20.54	12.56
3	6.02	9.01	3.54	5.84
4	1.94	2.68	1.83	2.01
5	1.75	1.80	1.14	2.51
6	22.78	22.19	21.77	21.80

Table 5.7: Average output queue length variation with push-type vehicle initiated dispatching strategies

Centre	Average output queue length			
no.	FCFS	MFCFS	SPT	FOR
1	0	0	0	0
2	1.16	0.39	1.07	0.88
3	1.16	0.95	0.77	0.84
4	1.07	0.88	1.01	0.80
5	1.04	0.85	0.70	0.65
6	1.43	1.25	1.08	1.09

describe the queue behaviour with respect to dispatching rules.

Average queue length v/s push-type vehicle initiated dispatching rules: Among the various source driven rules tested in the previous experiment for their throughput performance, FCFS, MFCFS, EJAT, SPT, and FOR rules are found to yield comparable performance at the optimal fleet size of 10 vehicles (see Figure 5.5). Among them also, MFCFS and EJAT rules yield nearly same throughput results at all fleet sizes. The NW rule meets throughput target at a much lower fleet size, whereas MOQS/mROQS, MPT, and FW rules satisfy the target at higher fleet sizes. Hence, for uniformity purpose, the rules which are tested in this experiment include FCFS, MFCFS, SPT, and FOR. At a fleet size of 11 vehicles, all the four rules yield 198 unit loads throughput per shift. Tables 5.6 and 5.7 summarize the simulation

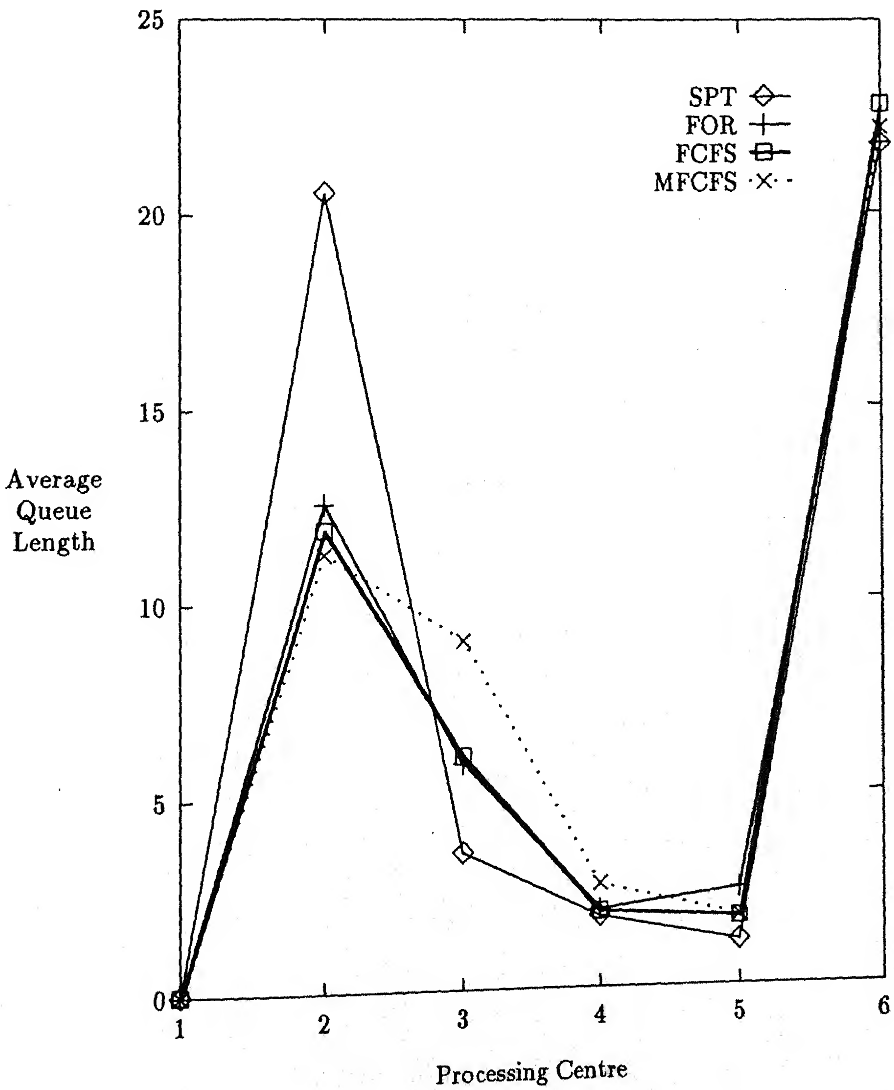

Figure 5.7: Average input queue length variation with push-type vehicle initiated dispatching strategies

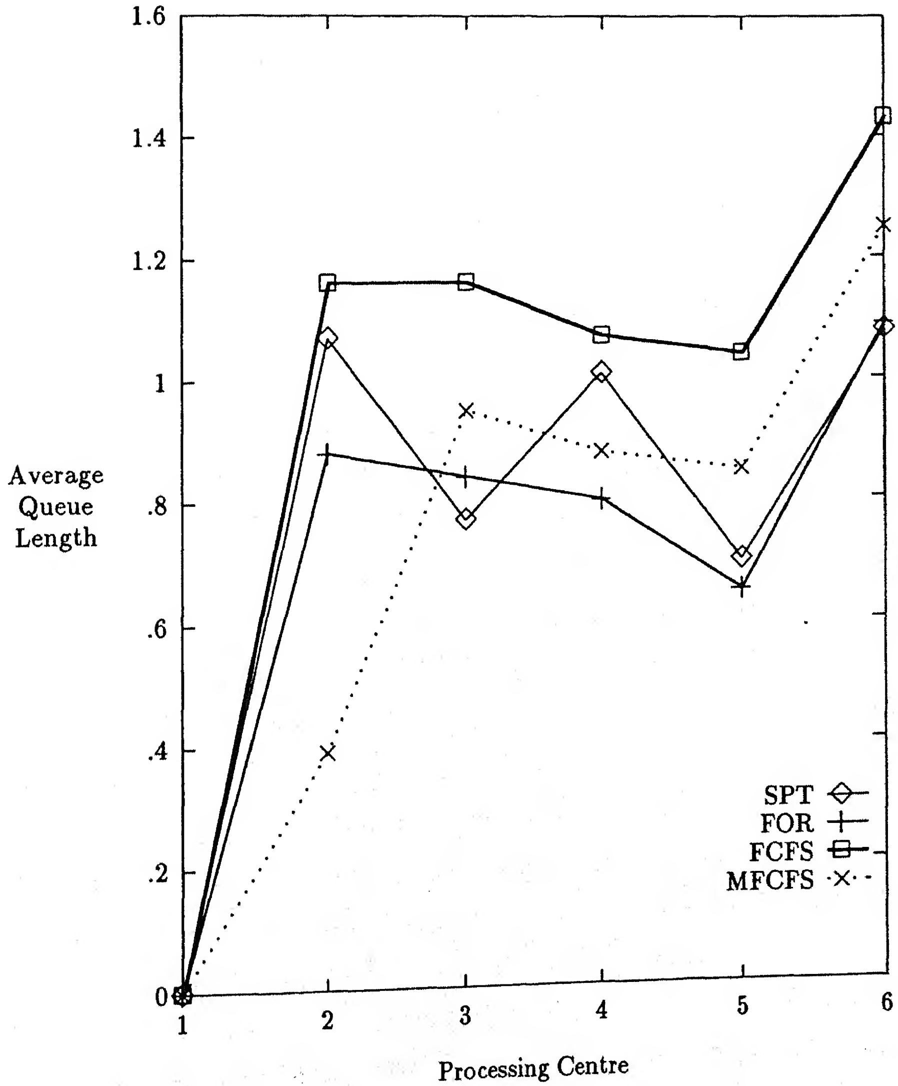

Figure 5.8: Average output queue length variation with push-type vehicle initiated dispatching strategies

results of these four rules for average input and output queue lengths respectiverly at each processing centre.

The same results are plotted in Figures 5.7 and 5.8 respectively. It is observed from these results that average queue length at input buffers at most of the centres is much higher than at output buffers. More jobs wait in the input buffers for their processing requirements, whereas fewer jobs spend time in output buffers awaiting pickups by vehicles. This indicates that at the P/H ratio of 3.107 (75:25), the machining subsystem is more critical than the material handling subsystem. The dispatching rules yield more variability in average queue lengths at centres 2 and 3. Centre 6 is more heavily loaded than other centres from processing as well as material handling point of view. It has a high buffer space requirement both for input and output buffers.

Average queue length v/s pull-type vehicle initiated dispatching rules: The above experiment is repeated with respect to the following demand driven rules — EIAT, mIQS, and MRIQS. These rules are observed to yield throughputs of 195 unit loads and above per shift at a fleet size of 11 vehicles (see Figure 5.6). The distance based rules ND and FD are not considered here for uniformity purpose, since the two rules yield comparable throughputs at very different fleet sizes. The simulation results are summarized in Tables 5.8 and 5.9, and plotted in Figures 5.9 and 5.10 for average input and output queue lengths respectively.

The results of Figure 5.9 indicate that there is a high variability in average input queue length at centre numbers 2 and 3, whereas the results for centres 4, 5, and 6 are consistent. There is a greater buffer space requirement at input buffer of centre 6. These observations are similar to those made for push-type rules. Figure 5.10 presents results for average output queue length. The variation pattern seen in this figure is different than that yielded by push-type rules. The pull-type rules yield more variable output queue lengths at centres 2, 3, 4, and 5, with MRIQS rule requiring high buffer space at centre 5.

As a result of comparison of average input/output queue lengths at each centre, the buffer space requirements can be assessed. Suitable dispatching rules can be adopted which not only meet the throughput target but also necessitate lower space

Table 5.8: Average input queue length variation with pull-type vehicle initiated dispatching strategies

Centre no.	Average input queue length EIAT	mIQS	MRIQS
1	0	0	0
2	24.86	21.00	10.00
3	8.21	8.77	4.73
4	1.52	2.16	3.23
5	1.74	0.90	1.66
6	18.13	18.43	21.15

Table 5.9: Average output queue length variation with pull-type vehicle initiated dispatching strategies

Centre no.	Average output queue length EIAT	mIQS	MRIQS
1	0	0	0
2	0.91	1.24	1.78
3	1.67	0.87	0.98
4	0.76	1.32	1.39
5	1.38	0.74	4.83
6	1.07	1.22	1.04

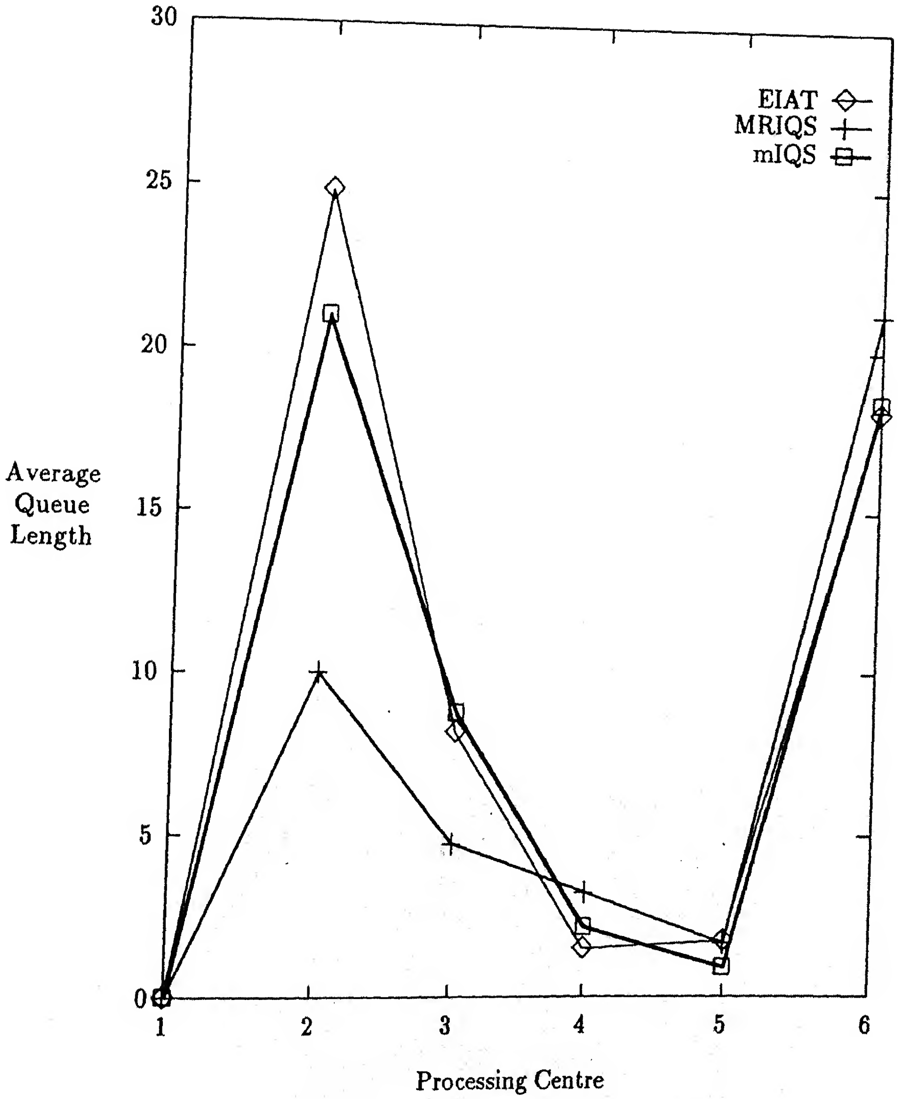

Figure 5.9: Average input queue length variation with pull-type vehicle initiated dispatching strategies

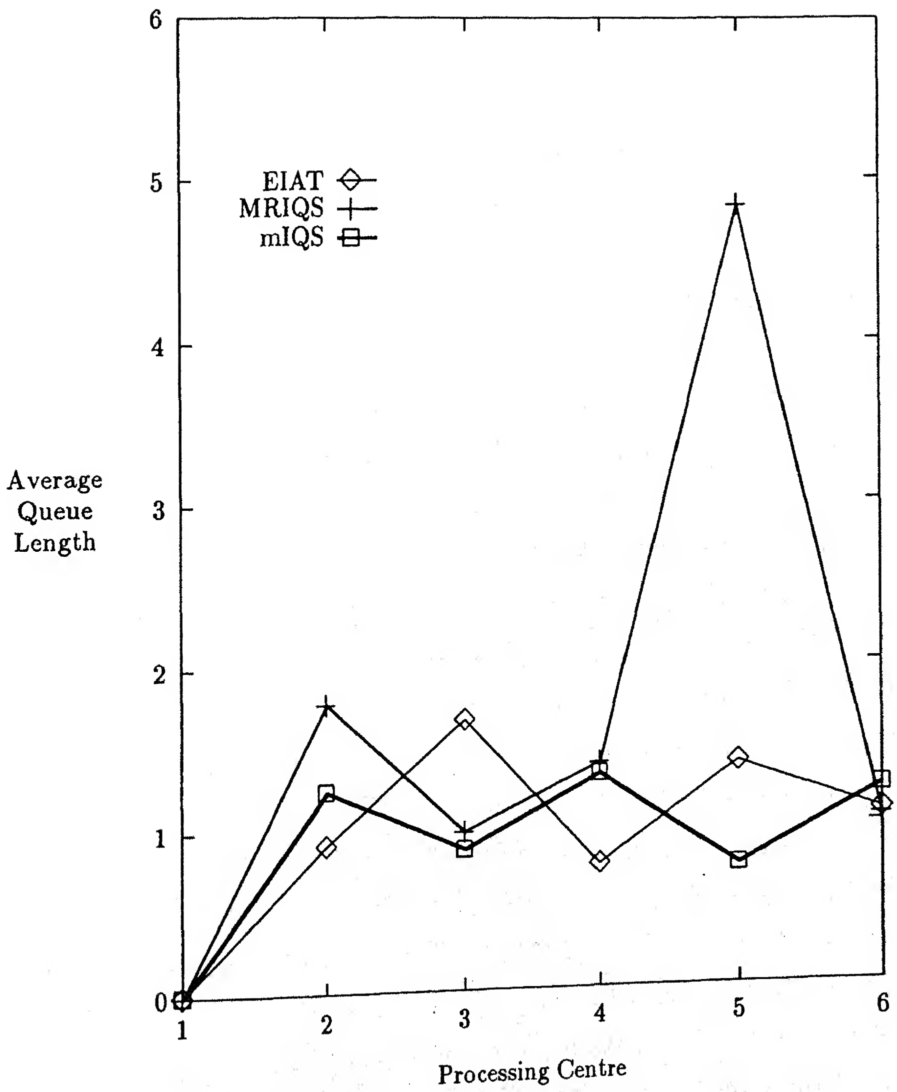

Figure 5.10: Average output queue length variation with pull-type vehicle initiated dispatching strategies

requirement at input/output buffers.

5.9 Conclusions

Vehicle dispatching is an important aspect of AGVS operational control. A vehicle dispatching strategy is a set of rules that have to be followed while deciding on either which vehicle or which unit load to choose for a particular transportation assignment. These rules are used for determining the sequence in which various routes will be visited. Most methods used for dispatching problem are heuristic in nature.

Several rules for dispatching AGVs in a job-shop with an existing layout are presented in this chapter. These include source driven (push-type) and demand driven (pull-type) vehicle initiated, and centre initiated dispatching rules. Simulation methodology is used for evaluating throughput potential of the facility under different dispatching rules, as well as for assessing the space requirements at input/output buffers at each centre. The characteristics of these rules are demonstrated under two shop operating conditions, namely capacitated and uncapacitated input/output buffers. It is demonstrated that push-type vehicle initiated rules which are derivatives of distance measures have several drawbacks. At finite buffer capacity, the NW rule induces shop locking conditions. The FW rule yields poor throughput rates irrespective of buffer capacity. The SPT rule does not fare well at finite buffers, but it yields a good throughput rate at infinite buffer levels, though requiring more space in input buffer at centre 2. The FCFS and MFCFS rules yield nearly same results at infinite buffers. The FCFS rule, however, leads to shop locking at finite buffers because of concentration of empty vehicles at centres with high activity levels. The MFCFS rule, on the other hand, distributes the vehicles evenly in the network. The FOR, mROQS, and EJAT rules yield higher rates of throughput irrespective of buffer space capacity, and also require minimal space at input/output buffers. Pull-type vehicle initiated rules do not yield consistent results for throughput rates as well as for buffer space requirements. Centre initiated dispatching rules do not affect the throughput results at all, since vehicles are rarely

idle to allow invoking of these rules. The simulation study also demonstrates how the vehicle dispatching problem and its associated resolution techniques can help in evaluation of buffer space requirements at each centre. This chapter demonstrates the importance of adopting a judicious combination of dispatching rules so as to meet the material handling needs of the system while avoiding shop locking conditions.

Chapter 6

Vehicle Route Planning and Traffic Management

6.1 Introduction

One of the major decision problems arising in the operation of an AGVS is vehicle routeing decision. The problem of vehicle route planning consists of the selection of a unique route for any given vehicle mission, in such a way that the vehicle reaches its destination using the shortest defined path. Kim and Tanchoco (1991) stated the problem environment for a conflict-free shortest time AGV routeing decision as follows. There are several vehicles in the system serving a predefined flow path network which consists of a set of nodes and a set of lanes. Nodes represent load transfer stations, intersections, parking lots, battery charging stations, and other important locations. Lanes can be unidirectional, bidirectional or mixed. There may be multiple lanes connecting the same pair of nodes if the traffic is heavy. A dispatch command issued to a vehicle includes a pair of source and destination nodes. Assuming the vehicle is currently located at the source node, the problem is then to find a route starting from the source and arriving at the destination as early as possible without disrupting other active travel schedules.

This chapter addresses the issue of vehicle route planning in details. The functions and requirements of a system controller are explained in the next section.

This is followed by a description of some heuristic rules for regulating vehicle traffic at nodes. The two salient approaches to route planning — static and dynamic — are then briefly reviewed from the available literature . The main thrust of the present work is development and testing of a proposed semi-dynamic time window constrained routeing strategy. Reserved time windows are placed on nodes indicating sequential crossing of nodes by the respective vehicles. Free time windows represent empty time slots available for vehicles to cross the nodes. Similarly, time windows representing direction of traffic flow are placed on the bidirectional arcs. Based on these time windows, Dijkstra's algorithm is applied to find the minimum blocking fastest routes for vehicles. A simulation study of the four flow path designs developed in Chapter 4 is then reported. The aim of the simulation experiment is to evaluate the system performance under the proposed routeing strategy vis-a-vis static routeing strategy.

6.2 System controller

An AGVS supervisory/system/traffic/transport controller is designed to handle route selection and manage vehicle traffic system in an organized and coherent manner. System management function incorporates the development of all policies necessary to control each vehicle in any possible situation. Traffic control and safety management is a system or vehicle ability to avoid collisions with other objects including other moving vehicles.

An intelligent model of a system controller should contain modules that track the status of AGVS network arcs, establish rules for contention regarding the use of arcs and provide for contingency routeing rules if required. The supervisory controller's main task is to satisfy transportation demands in a non-conflicting manner and in the shortest possible time. Design of system controller is a complicated task because of the dynamic nature of the manufacturing system. The decisions have to be made on-line, and they have to be fast and accurate. The main tasks of the system controller are as follows.

1. Vehicle selection (dispatching).

2. Route planning including determination of destination of the vehicle and the route it takes. The latter function entails determining the arrival and departure times of vehicles at each arc and node to ensure collision-free journey.

3. Empty vehicle management.

4. Priority control of various transport missions.

5. Vehicle tracking and routeing in such a way as to prevent shop locking.

6. Blocking zone management.

7. Priority control at junctions.

The guide path layout configuration has a major impact on the complexity of the system's control software. The more alternate routes and conflicting intersections there are in the guide path, the more complicated it is to control traffic in an effective way.

6.3 Regulation of vehicle traffic at nodes

Simultaneous or near-simultaneous arrivals at a node by multiple vehicles result in conflicts between the arriving vehicles as to which has right of way for crossing the node. Rules for vehicle crossing at intersections are concerned with monitoring and controlling traffic blocking situations at the nodes of the AGVS flow path network. The intersections of the arcs and the entrance/exit areas (P/D stations) of the centres are protected by invisible check zones. A check zone can accommodate only one vehicle at a time, and an accepted AGV captures it only for a fixed amount of time. During this time, all the vehicles which want to use the same zone must wait in their respective arcs or sidings available at the end of each respective arc. The right of use of the zones can be assigned according to several rules which can be implemented for resolving traffic conflicts at a node. Egbelu and Tanchoco (1982) suggested the following rules for implementation of the control measures.

1. FCFS: A vehicle arriving first at a node has the first right to cross it.

2. FCFS restricted to an engress arc: All the vehicles intending to enter one particular arc are allowed to clear the node first of all on FCFS basis.
3. FCFS restricted to an ingress arc: All the vehicles occupying one particular arc are allowed to clear the node first of all on FCFS basis.
4. Vehicle status: A loaded vehicle has the first right to clear the node vis-a-vis an empty vehicle.
5. Any other priority mission scheme.

In general, the centre initiated vehicle dispatching rules such as RV, LIV, and LUV, can also be applied to resolve vehicle interference situation at a node (Vosniakos and Mamalis 1990). Kim and Tanchoco (1991) discussed the possibility of allowing two or more vehicles to cross the check zone simultaneously under special cases if the space permits.

6.4 Static route planning

In a static approach to route planning the main criterion is to dispatch a vehicle by assigning it to the flow path route associated with minimum distance to its destination. The shortest distance between any two nodes in the system is computed and the vehicles are dispatched accordingly. Thus, the single objective function in such models is to minimize the distance travelled by the vehicles. The possibility of track congestion and vehicle blocking in an AGVS using static path planning is very high since same optimal routes are taken regardless of the traffic congestion status of the tracks. Such a system offers very little flexibility.

The traditional method for route planning of AGVs is to determine, in advance, all of the useful paths within the system, and store the information in a central computer until needed. The simulation strategy of Ashayeri *et al* (1985) employed Dijkstra's algorithm for computing the shortest path between two nodes. This information, in the form of a route matrix, was then stored in computer's memory and retrieved when needed.

Haines (1985) described a routeing algorithm that determined the correct turns an AGV would make while it was in motion. Making routeing decisions did not require a global map of the system's layout because a method of numbering nodes within the system which reflected a vehicle's natural path of flow was employed. This enabled the AGV to decide which turn to take at a decision point solely by knowing its destination node number, its current node number and the alternative candidate nodes' numbers. The algorithm is applicable when there exists a path through the system that passes exactly once through each intersection, buffer, and processing centre, and there are no more than two paths leaving any intersection. The algorithm is ideal for use in systems where the control of routeing is handled by distributed controllers functioning as peers as opposed to systems where distributed controllers are organized in a hierarchical manner with a central computer controlling the routeing.

Blair *et al* (1987) presented a two-phased heuristic algorithm for the near optimal routeing of AGVs which sought to organize material moves into tours with the objective of minimizing the maximum tour length (minmax) and thus distributing workload evenly among vehicles.

6.5 Dynamic route planning

AGVSs adopting dynamic path planning models offer a very high degree of flexibility. Such dynamic models have multiple objective functions and constraints, and take into account forecasting traffic in order to avoid congestion. This form of path planning is widely used in autonomous vehicles which operate under unknown domain.

The concept of conflict-free shortest-time AGV routeing was first introduced by Broadbent *et al* (1985) and Walker *et al* (1985). The Imperial College free ranging AGV (ICAGV) assumed the best path to be the path associated with the shortest distance to be travelled. The procedure employed Dijkstra's shortest path algorithm and generated a matrix describing node occupation times of vehicles. Potential conflicts were detected by comparing the occupation time of the new vehicle for each

node with the existing nodes' occupation times. Two types of potential conflicts in lanes were distinguished — a head-on conflict can occur when two vehicles travel in opposite directions, and a catching-up conflict can occur when two vehicles travel in the same direction but at different speeds. Unidirectional lanes can have only catching-up conflicts. Junction and catching-up conflicts were resolved by slowing down the vehicle to be scheduled. Head-on collisions were resolved by finding another shortest path excluding the congested segment, and changing the node occupation times and/or the speeds of the following vehicles. The procedure was suitable for the case of sensor blocking (a minimum headway maintained between two adjacent vehicles) which resulted in better utilization of the guide path network. It could be applied to both unidirectional and bidirectional network models.

The bidirectional flows represent highly tedious traffic control problems. Egbelu and Tanchoco (1986) proposed a heuristic to resolve node conflict in bidirectional traffic flow. They categorized conflicts as major conflicts (vehicles heading into each other) and minor conflicts, and further suggested that provision of vehicle buffering areas is important to resolve vehicular major conflicts in the use of an aisle.

Tanchoco *et al* (1987b) developed a LISP based intelligent real-time supervisory controller which was able to intelligently adapt to changes in the basic structure of the flow system operating at any given time in an AGVS consisting of a number of free ranging AGVs. They introduced the concept of a virtual tunnel. Each aisle could have multiple lanes allowing bidirectional flow, though each lane was essentially unidirectional. Multiple simultaneous crossing at intersections was also permitted. Taghaboni and Tanchoco (1988) presented an improved version of this model which could perform dispatching, routeing and scheduling tasks for free ranging vehicles. A scheduling algorithm for an AGVS has to be able to select a vehicle (dispatching) and perform route planning for the selected vehicle. Free ranging AGVs are capable of switching to another lane, overtaking slower vehicles and making U turns. These changes in speed, direction or lane of travel occur at check zones (control points). The designed controller was capable of detecting and preventing conflicts before they occurred. Once a collision was detected, it would explore different solutions to prevent the collision and would select that solution

that resulted in least delay time.

Koch (1988) presented a central, intelligent system director (controller) which could dynamically control vehicle dispatching rules and route plans by altering the priorities of unit loads (those waiting or those being processed), vehicles, and route network (flow path) segments. As opposed to a distributed on-board intelligence networking, it placed intelligence at the central controller level.

Gaskins and Tanchoco (1989) developed a C based vehicle system simulator, AGVSim-2, which could be used in the evaluation of control strategies of real-time free ranging vehicle supervisory controllers. The simulator allowed for many system configurations, bidirectional flow, multiple vehicle types and multiple loads on a vehicle. It performed the tasks of vehicle dispatching, dynamic route planning (varying speeds, avoiding collisions, etc.) and scheduling. This enhanced version of AGVSim (Egbelu and Tanchoco, 1983) featured a more flexible design capable of evaluating system control strategies for a wider range of system configurations.

Collision avoidance is the process whereby an AGV plans (or a central controller plans for it) its trajectory (path) in such a way as to avoid spatial conflict with any other object in its work space (known or unknown, and stationary or moving object). If the position of all obstacles at all times are known, collision avoidance can be performed in an off-line manner before motion begins. Obstacles whose presence and position are not previously known, or those that are moving in an unpredictable manner, requires on-line collision avoidance methods.

Cesarone and Eman (1989) described a research effort in the area of collision avoidance path planning for AGVs or mobile robots. They discussed the general principle of dynamic programming and its modification to fit the AGV routeing problem. They tackled the find-path problem, blending the shortest-path and safest-path approaches. Their dynamic programming modification employed a user defined performance index which could be adjusted to yield a compromise between the shortest and the safest extremes.

The labelling algorithm proposed by Huang *et al* (1989) assigned labels to free time windows defined for each node rather than to physical nodes. The algorithm treated the physical arcs of the original guide path as nodes in the converted network.

The journey time on an arc of the original network was converted to the dwell time on the corresponding node of the converted network. The algorithm was applicable to both unidirectional and bidirectional flow networks, and the shortest time route found by the algorithm allowed for both cycles and loops in the final solution (a cycle in a graph is a path whose intermediate nodes are all distinct but which starts and ends at the same node, and a loop is a cycle with only one arc). The application of this algorithm is restricted to the case where zone blocking is used for traffic control.

Fujii *et al* (1989) presented a routeing control algorithm to determine, using a branch-and-bound method, a non-conflicting path for an AGV. The routeing problem was regarded as a shortest path finding problem on a network with time windows. The concepts of modified time windows and shifted time windows were introduced to regulate an AGV's travelling schedule. Time windows were placed on arcs as well as nodes so as to constrain the AGV both to start and to arrive at the node or the arc within the specified time windows. The way time windows were defined on arcs allowed sensor blocking. The algorithm was good for both unidirectional and bidirectional models, and the results could include cycle but not loop in the final route.

Zeng *et al* (1991) applied Petri net modelling approach to detect AGV conflict in a dynamic vehicle routeing environment. They used coloured timed Petri nets to depict a "place" node for mapping vehicle routes (a path, an intersection, or a station) as a shared resource, and a set of "tokens" for representing the state of places (availability of a path, station, or vehicle for entry). The Petri net safety problem of detecting deadlocking in the net was used for identification of vehicle conflict in route planning. If a conflict was detected then the routeing plan was aborted and corrective measures included dispatching another vehicle present at a different location, or adopting different routeing or varying the vehicle speeds, if possible.

Kim and Tanchoco (1990, 1991) presented an efficient algorithm for finding conflict-free shortest time routes for AGVs moving in a bidirectional flow path network. The proposed algorithm was based on Dijkstra's shortest path method. It maintained, for each node, a list of time windows reserved by scheduled vehicles and

a list of free time windows available for vehicles to be scheduled. They introduced the concept of time window graph in which the node set represented the free time windows and the arc set represented the reachability between the free time windows. The algorithm routed the vehicles through the free time windows of the time window graph instead of the physical nodes of the flow path network.

6.6 A semi-dynamic time window constrained route planning approach

A semi-dynamic time window constrained vehicle routeing algorithm is developed and presented in this section. The algorithm takes into account the current traffic status to calculate minimum blocked fastest routes for vehicles. It is a dynamic algorithm because it considers alternate routes while selecting a unique route for a vehicle mission. Whereas static planning approach always results in selection of the same route between two locations, the proposed algorithm may yield different routes at different times depending on the traffic status in the network. On the other hand, the algorithm is only semi-dynamic because once a route is selected for a vehicle mission, it is then adhered to and is not amenable to future changes. In other words, once a space-time path is selected, it becomes static to that extent. A pure dynamic strategy would be one in which routeing decisions are made at each node in the vehicle journey rather than only once at the time of start of the journey.

The proposed algorithm, still assumes the presence of adequate vehicle buffering sidings for elimination of head-on conflicts between vehicles, as is done for static approach. In this sense, the algorithm does not have any economizing effect on siding space consideration. If no provision is kept for temporal vehicle bufferings, then intelligent methods of avoiding vehicle blocking have to be devised and employed. One such method is to divert the blocked vehicle to other less congested arcs and releasing it back on its main course when the traffic situation becomes clear. Such vehicle route planning under dynamic routeing approach may generate vehicle routes which are distance-wise longer and may contain cycles and loops in the selected routes (Kim and Tanchoco 1991). The proposed algorithm does not produce cycles

or loops in vehicle routes since adequate vehicle buffering sidings are assumed to be present in order to avoid head-on conflicts between vehicles. The traffic status is modelled by maintaining linked lists of scheduled entry and exit times of vehicles at each node and each arc of the network.

6.6.1 Time windows at nodes

The time window at a node is characterized as being either reserved or free. A reserved time window is described by a pair of scheduled entry and exit times of a vehicle which is to occupy the node and enter into a subsequent outgoing arc. The time interval is exclusively reserved by that vehicle, and other vehicles are not allowed to occupy the node during this time. Furthermore, the interval between entry and exit times of a reserved time window can be zero, implying that the vehicle does not physically occupy the node but makes an about turn in the arc in whose siding it is then located. Such reversal in flow direction in an arc can occur only if the arc is a bidirectional one. The free time windows between the reserved time windows are available for scheduling other vehicle crossings.

6.6.2 Time windows at arcs

An immediate question is how to determine whether the vehicle can reach from one time window at a node to another one at the next node. The reachability from one node to the other depends on directionality of the arc joining the two nodes. If the arc is unidirectional one, then the vehicle can immediately enter the arc and proceed to the other end keeping a minimum headway distance between a preceding vehicle, if any. On the other hand, if the arc is bidirectional, then the flow direction scheduled in the arc at that time is to be checked. In order to do this, time windows are placed on arcs as well. A time window on an arc is described by a pair of entry and exit times together with a flow direction in the arc. If the entrant vehicle is to proceed in the same direction as that of the time window (downstream), then it is allowed to go ahead keeping a minimum headway distance between itself and any preceding vehicle. The entry and exit times of the time window are suitably

modified in this case. On the other hand, if entrant vehicle desires to occupy the arc in a direction opposite to that of the time window, then it has to wait till the upstream traffic in the arc is cleared. A new time window in opposite direction is placed on the arc in this case.

6.6.3 Illustrative example

A typical situation is exemplified in Figure 6.1. The flow path network shown in Figure 6.1(a) is a portion of Bi-III network composed of all bidirectional arcs (Figure 4.3). In this example, two vehicles v_1 and v_2 have been scheduled to traverse the partial network as shown below.

<u>Current schedules for v_1 and v_2</u>

v_1: $\rightarrow$ $(n_{11}, [10.50, 10.65])$ $\rightarrow$ $(a_{16}, [10.65, 11.50])$ $\rightarrow$
$(n_5, [11.50, 11.65])$ $\rightarrow$ $(a_7, [11.65, 12.25])$ $\rightarrow$

v_2: $\rightarrow$ $(n_{11}, [10.00, 10.15])$ $\rightarrow$ $(a_{17}, [10.15, 11.00])$ $\rightarrow$
$(n_{12}, [11.00, 11.15])$ $\rightarrow$ $(a_{18}, [11.15, 11.75])$ $\rightarrow$

Notation: (node or arc, [entry time, exit time])

Figure 6.1(b) graphically shows the entry and exit times of these vehicles at the above mentioned nodes on their routes. Figure 6.1(c) is the corresponding time window representation at different arcs traversed by these vehicles. In this situation, it is required to route vehicle v_3 from node 4 to node 11 starting at time 10.00. The aim is to schedule vehicle v_3 to reach node 11 as early as possible with minimum blocking delay encountered on its way. By a careful inspection, the two alternative routes which can be taken by vehicle v_3 can be represented as follows.

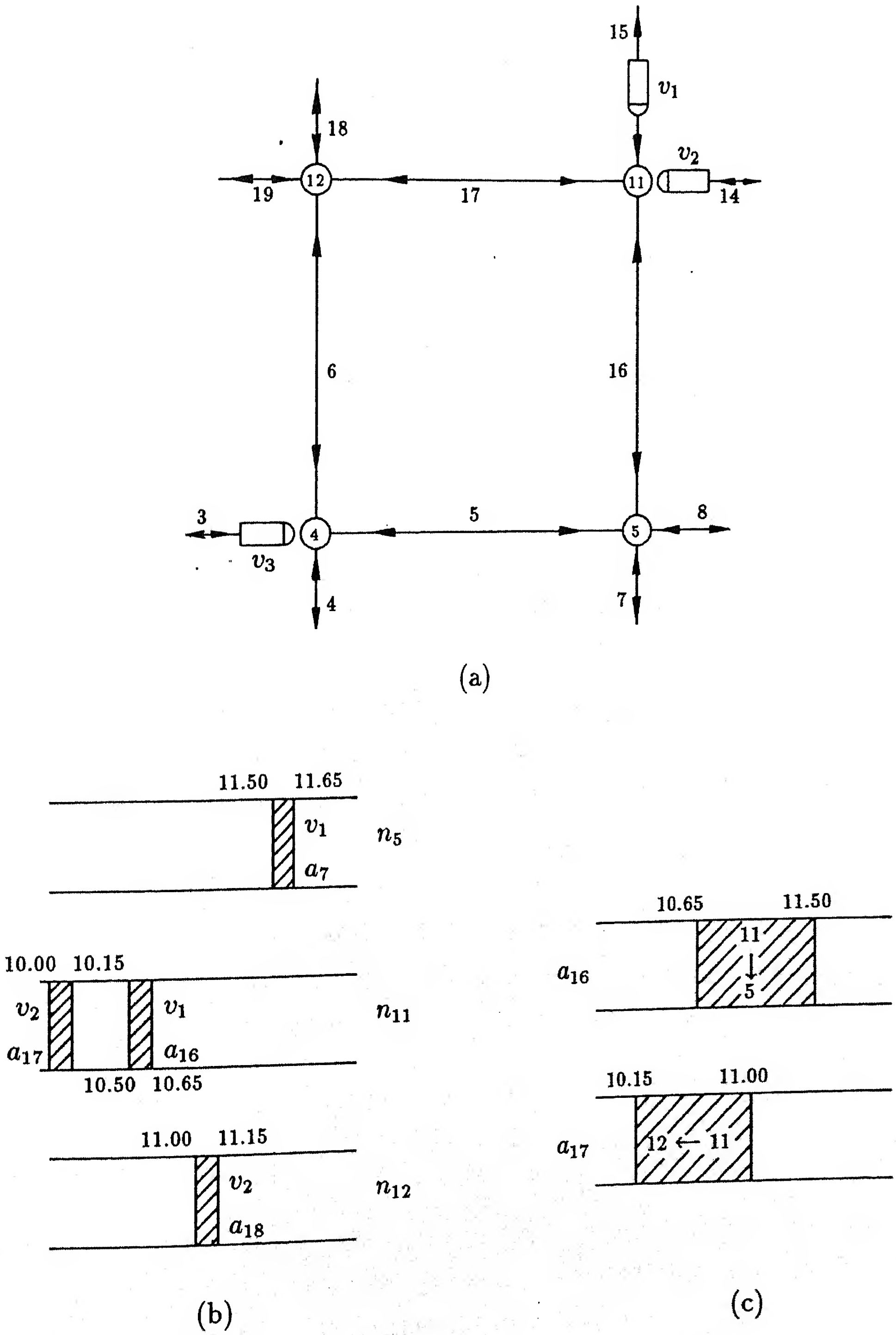

Figure 6.1: Example of time windows

<u>1st route for v_3</u>

v_3: $\rightarrow$ $(n_4, [10.00, 10.15])$ $\rightarrow$ $(a_5, [10.15, 11.00])$ $\rightarrow$ blocked $\rightarrow$ $(n_5, [11.65, 11.80])$ $\rightarrow$ $(a_{16}, [11.80, 12.65])$ $\rightarrow$

<u>2nd route for v_3</u>

v_3: $\rightarrow$ blocked $\rightarrow$ $(n_4, [10.15, 10.30])$ $\rightarrow$ $(a_6, [10.30, 11.15])$ $\rightarrow$ $(n_{12}, [11.15, 11.30])$ $\rightarrow$ $(a_{17}, [11.30, 12.15])$ $\rightarrow$

Static approach

In a static route planning approach, vehicles follow predetermined routes when going from one location to another. Such routes may either be stored in computer memory, or computed by applying Dijkstra's algorithm. The latter approach has been used in the previous chapters. The drawback of static routeing is that vehicles will always follow the shortest distance path to their destinations regardless of traffic status on these routes. The approach does not explore alternate routes even though there may be multiple shortest distance paths, as it happens in the case exemplified above. In the situation illustrated, there are two paths of equal distance for going from node 4 to node 11. The static routeing approach fixes one of them as the route to be always taken by the vehicles. Assuming that that predetermined path is $(n_4 \rightarrow n_5 \rightarrow n_{11})$, vehicle v_3 will be scheduled according to the 1st route. This route entails a blocking delay of 0.65 minutes for vehicle v_3 at node 5 in order to clear upstream traffic in arc 16.

Dynamic approach

A clear advantage of dynamic route planning approach is that it takes into consideration alternate paths while making routeing decisions, even though the paths may be of unequal lengths. From the situation illustrated above, it is observed that by purposefully delaying the start of vehicle v_3 at node 4 by 0.15 minutes

and taking the 2nd route, the vehicle can be scheduled to reach node 11 via path ($n_4 \rightarrow n_{12} \rightarrow n_{11}$) at time 12.15 which is 0.50 minutes ahead of what can be achieved by the 1st route. It is this consideration of alternate paths that imparts dynamic nature to the routeing approach. It has been exploited in the proposed algorithm to calculate minimum blocked fastest routes for AGVs.

6.6.4 Proposed Algorithm

The algorithm routes the vehicle to be scheduled through the time windows instead of physical nodes and arcs. Let a time window at the nth node be denoted by $[t_{n_b}, t_{n_e}]$, where t_{n_b} is the beginning time and t_{n_e} is the end time of the time window. Likewise, let a time window at the ath arc be denoted by $[t_{a_b}, t_{a_e}]$. It is required to schedule a vehicle, at time t_{now}, to cross the nth node and travel in the ath arc in order to reach its other end. The algorithm seeks to find a time interval $[x, y]$ within the free windows in the set $\{[t_{n_b}, t_{n_e}]\}$ such that the vehicle can be scheduled to occupy the node during this time, and further, can continue to move ahead in the arc and occupy it for $[y, z]$ period of time. The flowchart of the algorithm is shown in Figure 6.2. The algorithm consists of the following steps.

Step 0: Start with the required input.

Step 1: Find the node occupation interval. If the vehicle is to about turn, the interval is zero; otherwise it is equal to the node crossing time.

Step 2: Find the first free time at the nth node such that the vehicle can be accommodated.

Step 3: Calculate time intervals $[x, y]$ and $[y, z]$ which indicate the vehicle's occupation times at the node and the arc respectively.

Step 4: From the list of time windows at the ath arc, find the flow direction during time interval $[y, z]$. If the flow direction is the same as that of the vehicle, go to step 6; otherwise go to the next step.

Step 5: Modify the time intervals $[x, y]$ and $[y, z]$ in order to clear traffic in opposite direction. Go to step 2.

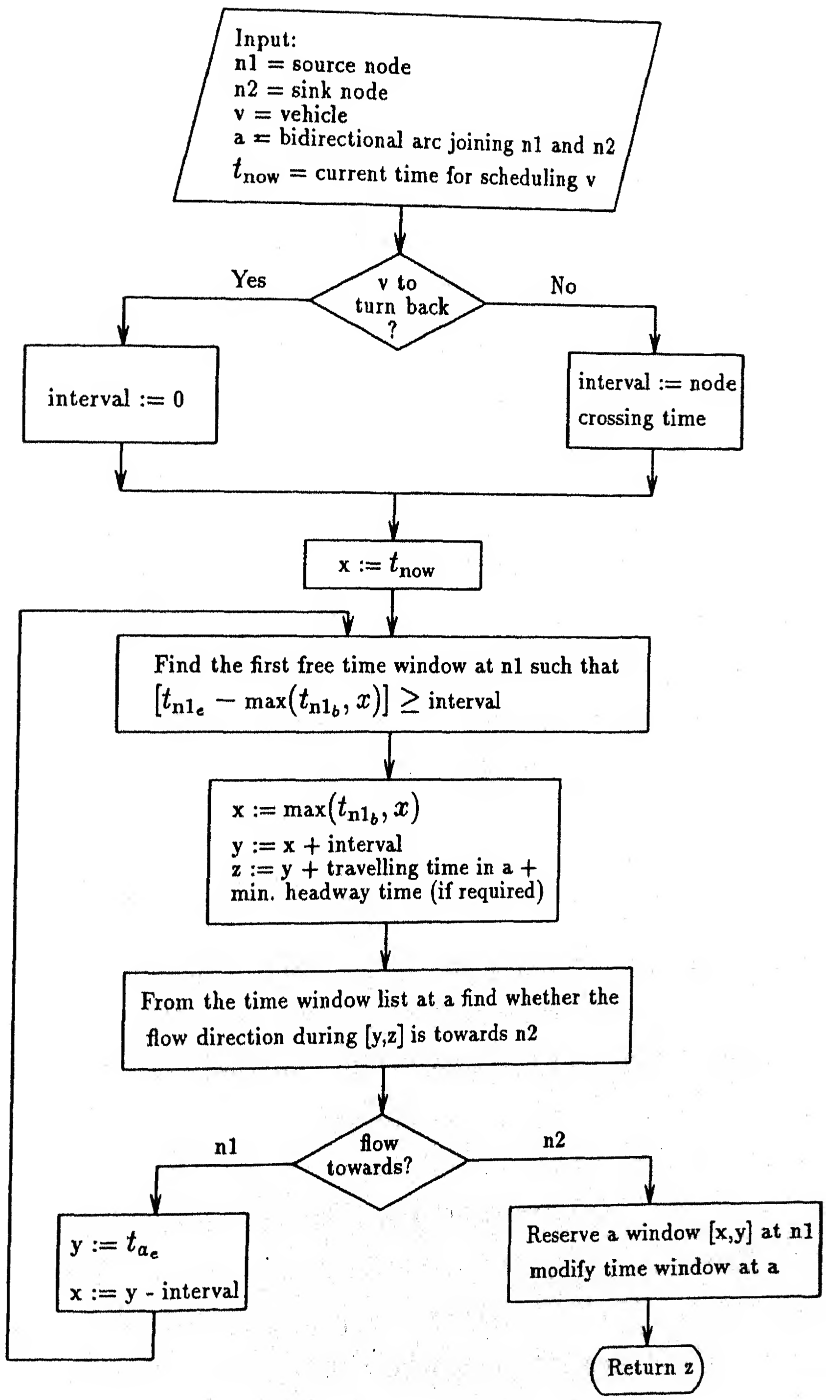

Figure 6.2: Flow chart for the proposed routeing algorithm

Step 6: Reserve a time window $[x, y]$ at the node. Modify or create the time window at the arc.

Step 7: Return with z as the time to reach the next node.

The following two observations can be made about the proposed algorithm.

1. Once the vehicle leaves a node, it is to continue its journey unstopped till it reaches the next node. It cannot stop in between in the arc, though it can reduce its speed in order to keep a minimum headway distance between itself and any preceding vehicle. In other words, the newly created reserved time window at the node and the corresponding time window at the arc have to be contiguous.

2. The traffic rule at the nodes is no longer FCFS. In the static routeing approach vehicles arriving at a node simultaneously or near-simultaneously cross the node on FCFS basis. This, however, is no longer applicable in the proposed approach. Crossing of nodes by the vehicles is regulated by the sequence of time windows imposed at nodes and arcs.

6.7 Simulation study

The above discussed algorithm is applied on the four alternative flow path designs of Chapter 4 (Uni, Bi-I, Bi-II, and Bi-III). The aim of the simulation study in this chapter is to observe the impact of the proposed routeing algorithm vis-a-vis the static routeing approach when the amount of bidirectionality is increased in the network. Shop throughput rate and vehicle activity time distribution are taken as the measures of performance. The vehicle dispatching rules include vehicle initiated push-type EJAT rule, and centre initiated NV rule. The other experimental conditions remain unchanged from the previous chapters. The throughput performances of the four flow path designs under the proposed routeing strategy are represented in Table 6.1. Figures 6.3 to 6.6 compare the throughput potentials of each of the four flow path designs under the impact of the proposed vis-a-vis static routeing strategies.

Table 6.1: Throughput performance of various flow path designs under the proposed routeing strategy

No. of	Average throughput rate			
AGVs	Uni	Bi-I	Bi-II	Bi-III
8	135.75	139.00	147.00	158.00
9	151.75	157.25	167.75	176.00
10	172.00	176.00	182.75	190.75
11	187.25	187.00	192.50	192.25
12	*	192.50	*	190.00
13	*	*	195.00	*

* Shop locking encountered

It is observed from these plots that the dynamic approach to route planning has no significant effect on throughput performance for Uni and Bi-I flow path designs. This is explained by the fact that since all or nearly all of the arcs in the network are unidirectional, the possibility of head-on conflicts between vehicles is totally eliminated. This avoidance of vehicle interference is achieved at the cost of loss in flexibility in terms of alternate routes a vehicle can take in order to reach its destination. The fewer are the alternate routes available, the lesser will be the advantage to be obtained by applying dynamic routeing strategy. As the amount of bidirectionality is increased in the network (rendering more number of arcs as bidirectional), more number of alternate routes become available and the dynamic routeing strategy gets opportunity to exhibit its enhancing effect on system throughput rate. This is evident for Bi-II and Bi-III flow path designs. Though, the optimal fleet sizes still remain 11, 11, 11, and 10 vehicles for Uni, Bi-I, Bi-II, and Bi-III flow path designs respectively (see Chapter 4), yet the throughput performances of Bi-II and Bi-III flow path designs indicate higher rates when dynamic routeing strategy is used.

Simulation results for vehicle activity time distribution for the four flow path designs under dynamic routeing strategy are summarized in Table 6.2 and plotted in Figures 6.7 to 6.10. These results are compared with those for static routeing

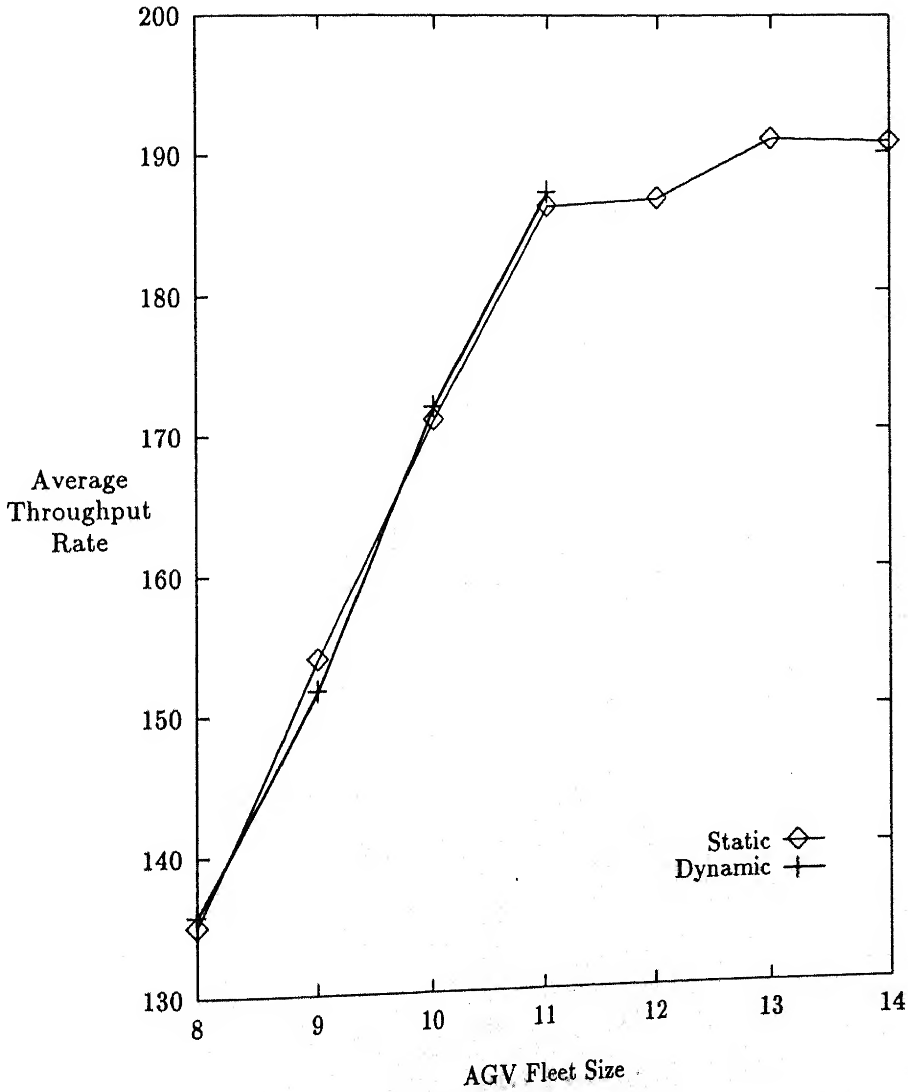

Figure 6.3: Effect of routeing strategy on throughput potential of Uni flow path design

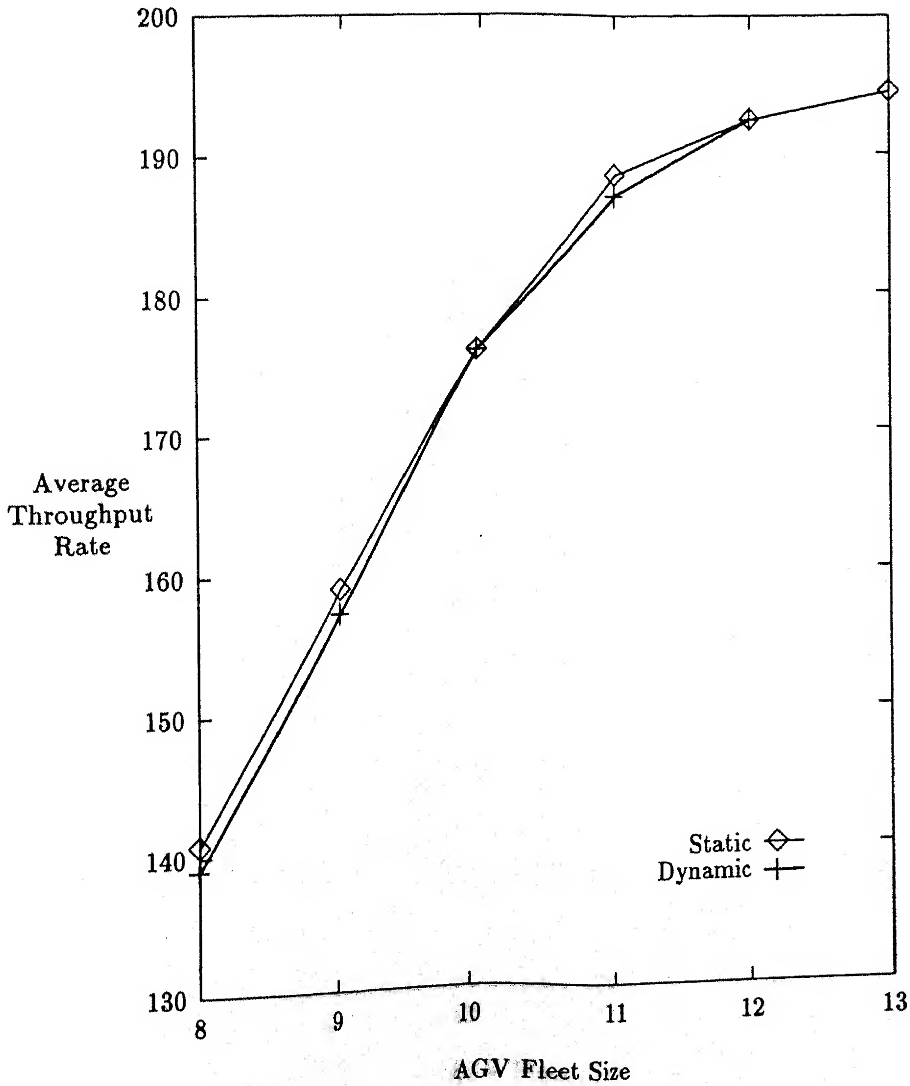

Figure 6.4: Effect of routeing strategy on throughput potential of Bi-I flow path design

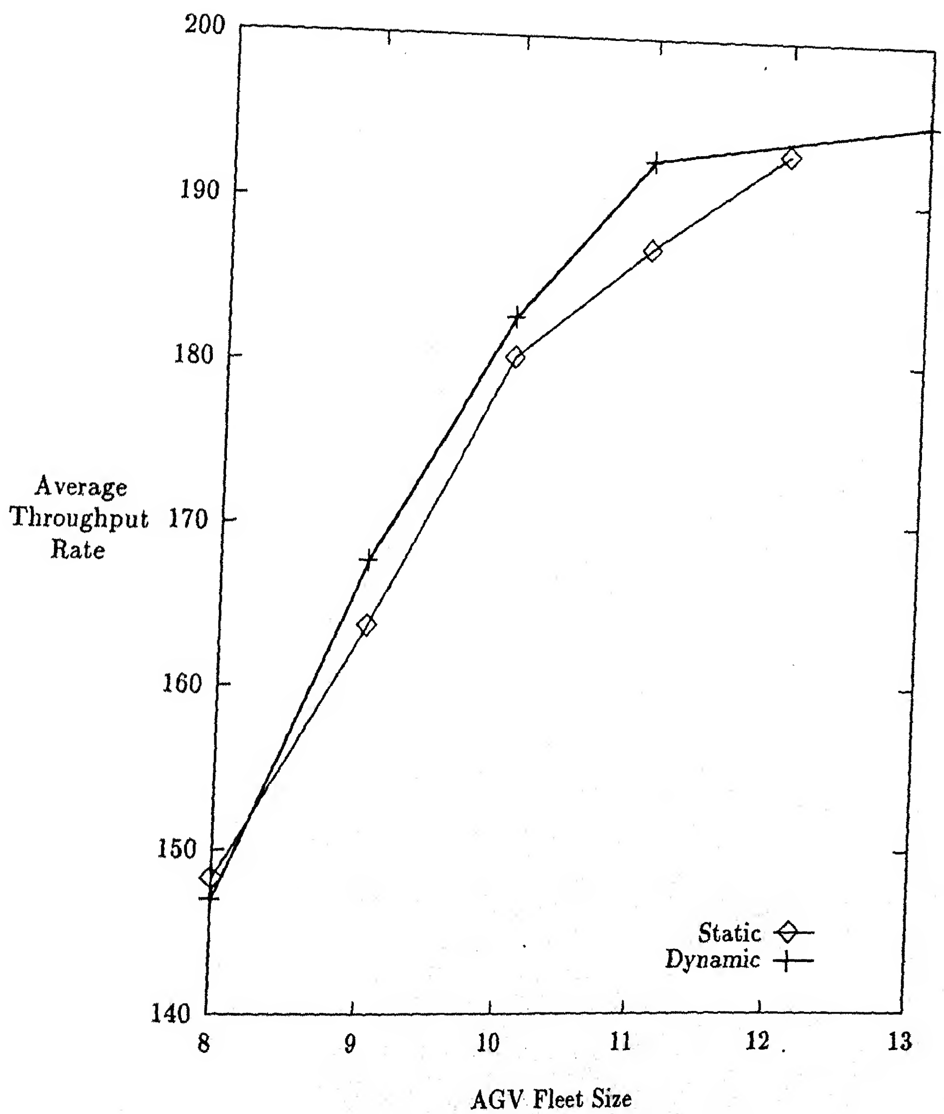

Figure 6.5: Effect of routeing strategy on throughput potential of Bi-II flow path design

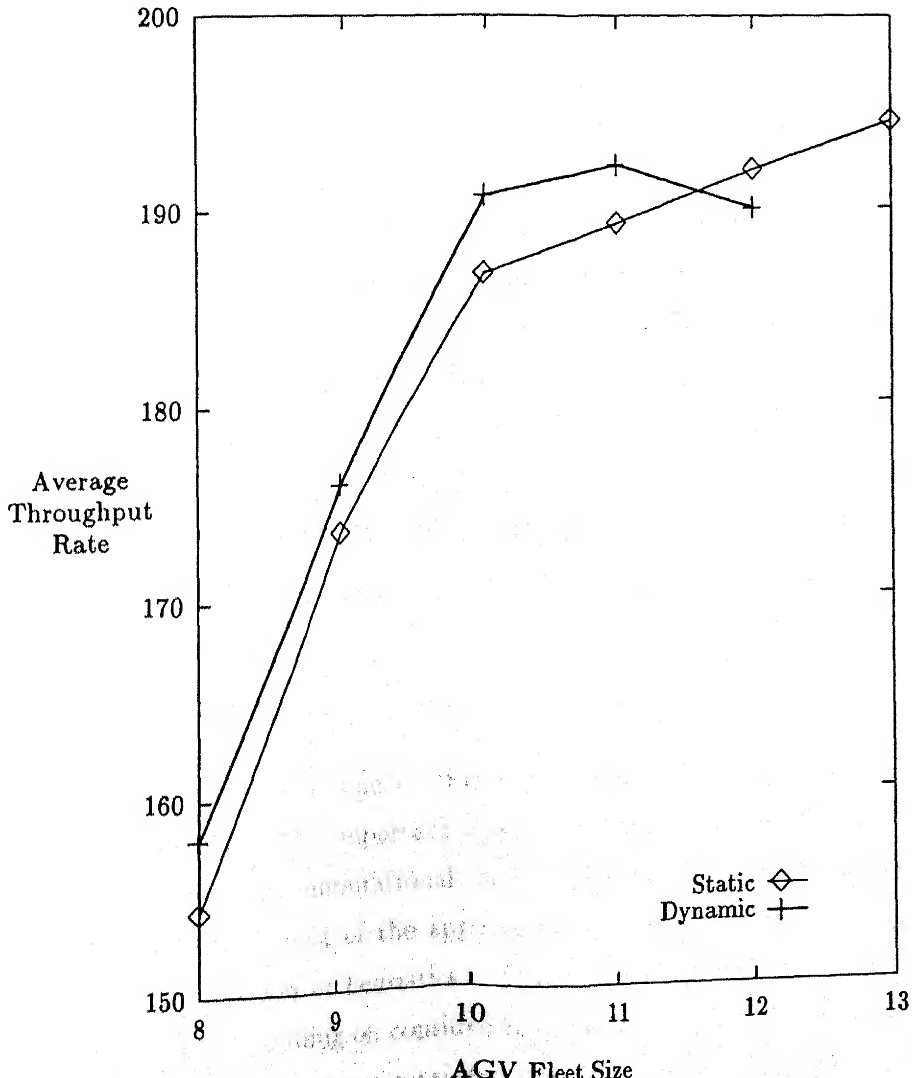

Figure 6.6: Effect of routeing strategy on throughput potential of Bi-III flow path design

(Figures 3.5, 4.7 to 4.9). The comparison shows that there is no significant difference between the results of the static and the proposed routeing strategies for Uni and Bi-I flow designs. This substantiates the above explanation for throughput performance of the two flow designs. Since all or most of the arcs in the network are unidirectional, the proposed routeing strategy has no alternate equal distance routes to consider, and thus fails to yield any improvements in throughput rates as well as vehicle activity time distributions. On the other hand, Bi-II and Bi-III flow designs incorporate multiple shortest distance paths in the network. The results indicate that by adopting the proposed routeing strategy there is a reduction in percent time a vehicle remains blocked (from 10% to 5%). Since the routeing approach evaluates all the alternate routes before selecting a unique route for a vehicle mission, and since minimum blocked fastest routes are selected, the result is a considerable reduction in overall traffic congestion status in the network. In fact, by selecting minimum blocked routes, the proposed strategy helps in distributing the vehicles evenly in the AGVS network. The reduction in blocking time makes the vehicles available for a longer time for loaded and empty travels, thereby helping to improve the throughput performance of the system.

6.8 Conclusions

Vehicle routeing decision is one of the key decisions for operational control of an AGVS. It addresses the important system behaviour of vehicle blocking phenomenon. Due to the computational complexity of the generic routeing problem which is NP-hard, most of the approaches to solve vehicle routeing problem rely mainly on simulation or heuristics. The approaches are broadly classified as static and dynamic depending on consideration of one or more number of objective functions. The dynamic strategy considers traffic status as well, besides travelling distances, while calculating the fastest routes for vehicles. A semi-dynamic vehicle routeing strategy based on time windows has been developed and presented in this chapter. The simulation study of various flow path designs demonstrates that as more arcs in the AGVS network are configured bidirectional, the vehicle blocking

Table 6.2: Vehicle activity time distribution for various flow path designs under dynamic routeing strategy

No. of AGVs	Vehicle activity time (%) Load handling	Empty travel	Waiting	Blocked
		Uni		
8	55.83	42.73	0	1.45
9	55.54	42.66	0	1.81
10	55.68	42.35	0	1.97
11	55.20	41.82	0.81	2.17
		Bi-I		
8	55.52	41.85	0	2.62
9	55.55	41.30	0	3.15
10	55.31	41.40	0.10	3.18
11	53.71	38.90	3.91	3.49
12	50.78	33.64	12.32	3.25
		Bi-II		
8	55.32	38.82	0	5.87
9	55.38	37.90	0.	6.72
10	54.42	37.38	0.95	7.11
11	52.28	34.96	5.49	7.29
13	45.14	24.09	25.09	5.62
		Bi-III		
8	56.74	37.23	0	6.04
9	56.23	37.17	0	6.61
10	55.20	35.06	2.94	7.30
11	50.73	29.64	12.94	6.73
12	46.09	22.52	26.05	5.39

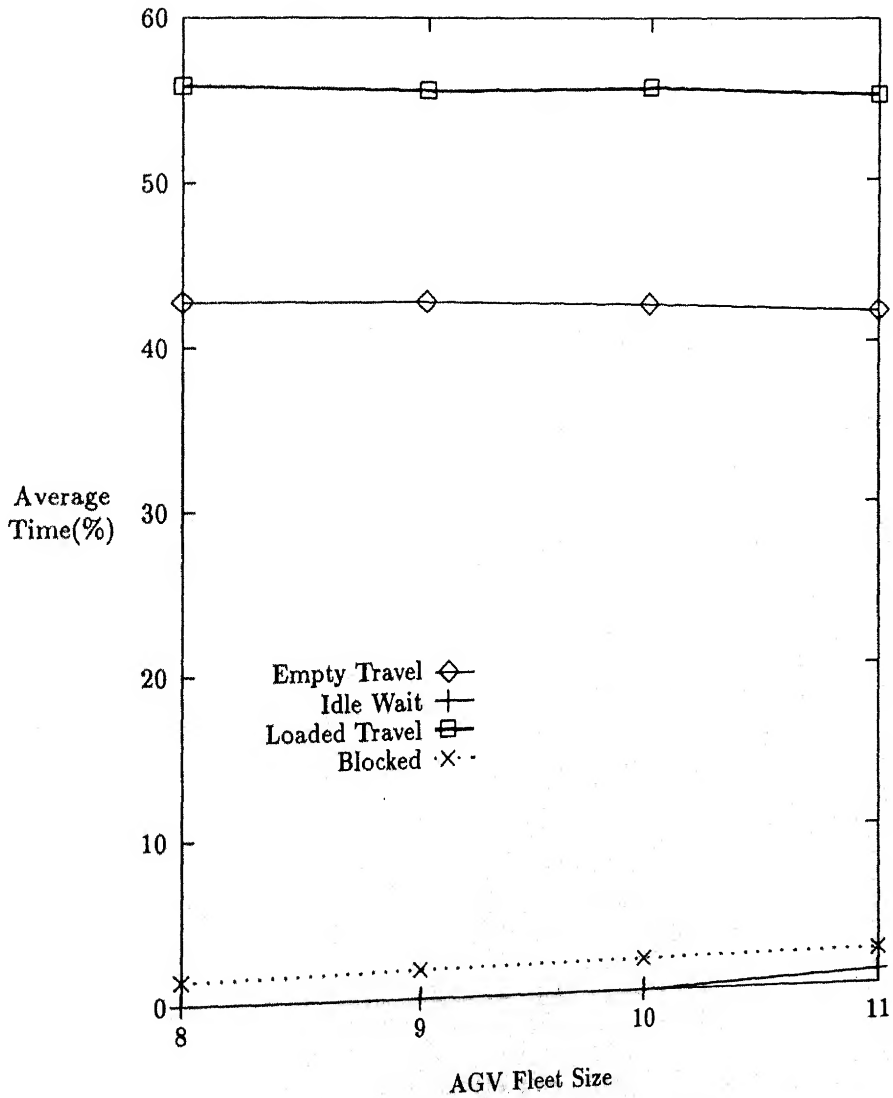

Figure 6.7: Distribution of vehicle activity time for Uni flow path design under the proposed routeing strategy

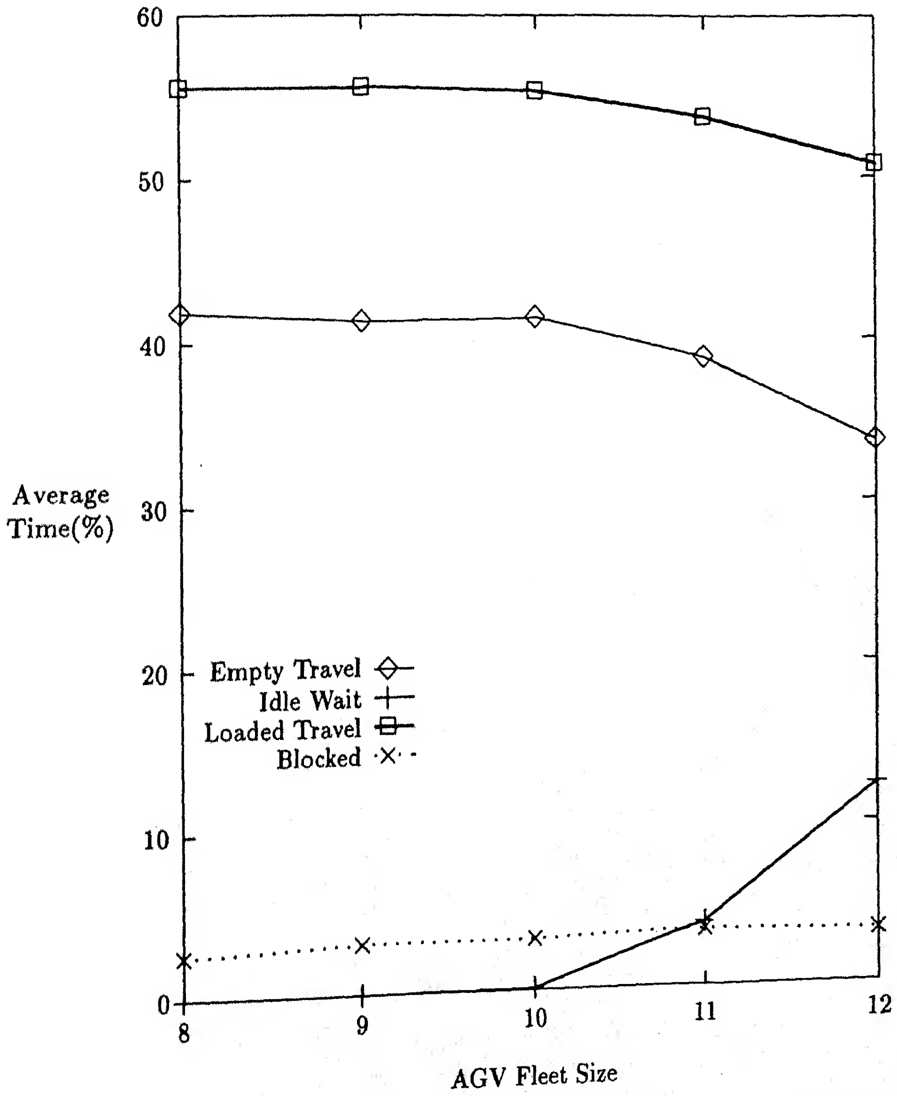

Figure 6.8: Distribution of vehicle activity time for Bi-I flow path design under the proposed routeing strategy

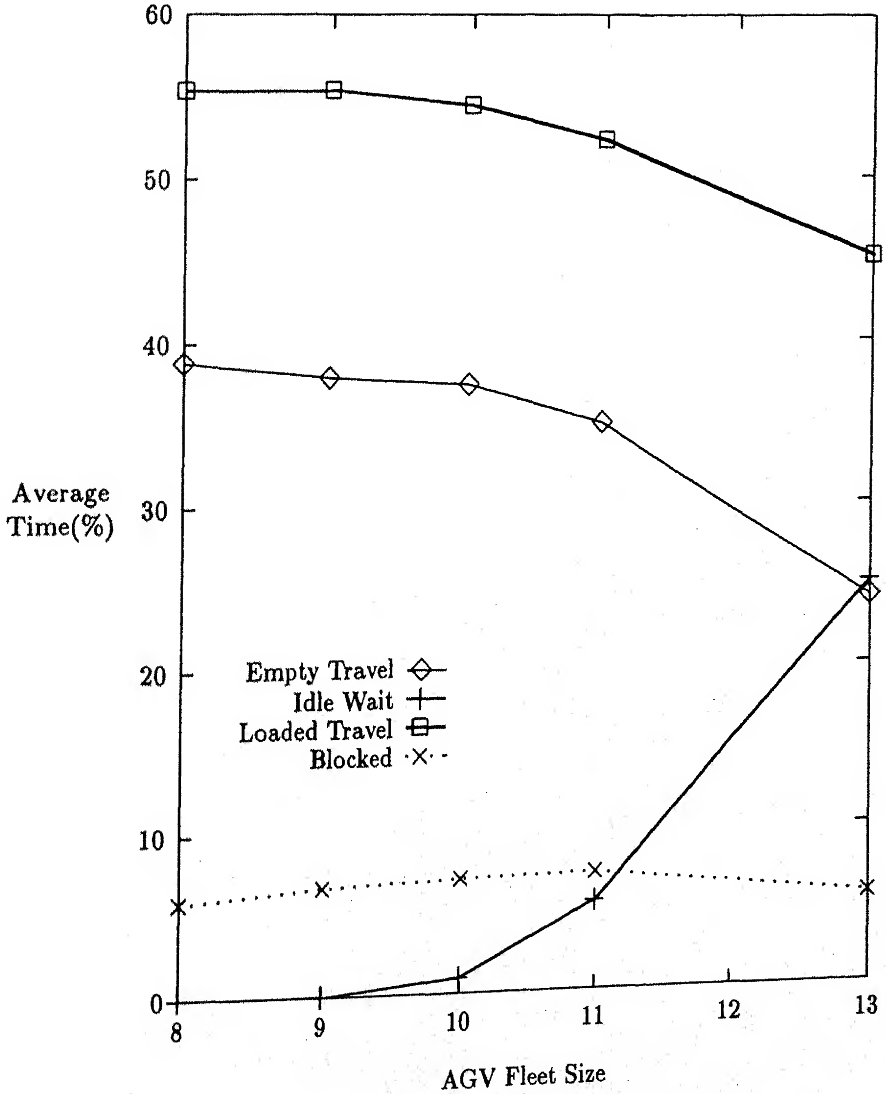

Figure 6.9: Distribution of vehicle activity time for Bi-II flow path design under the proposed routeing strategy

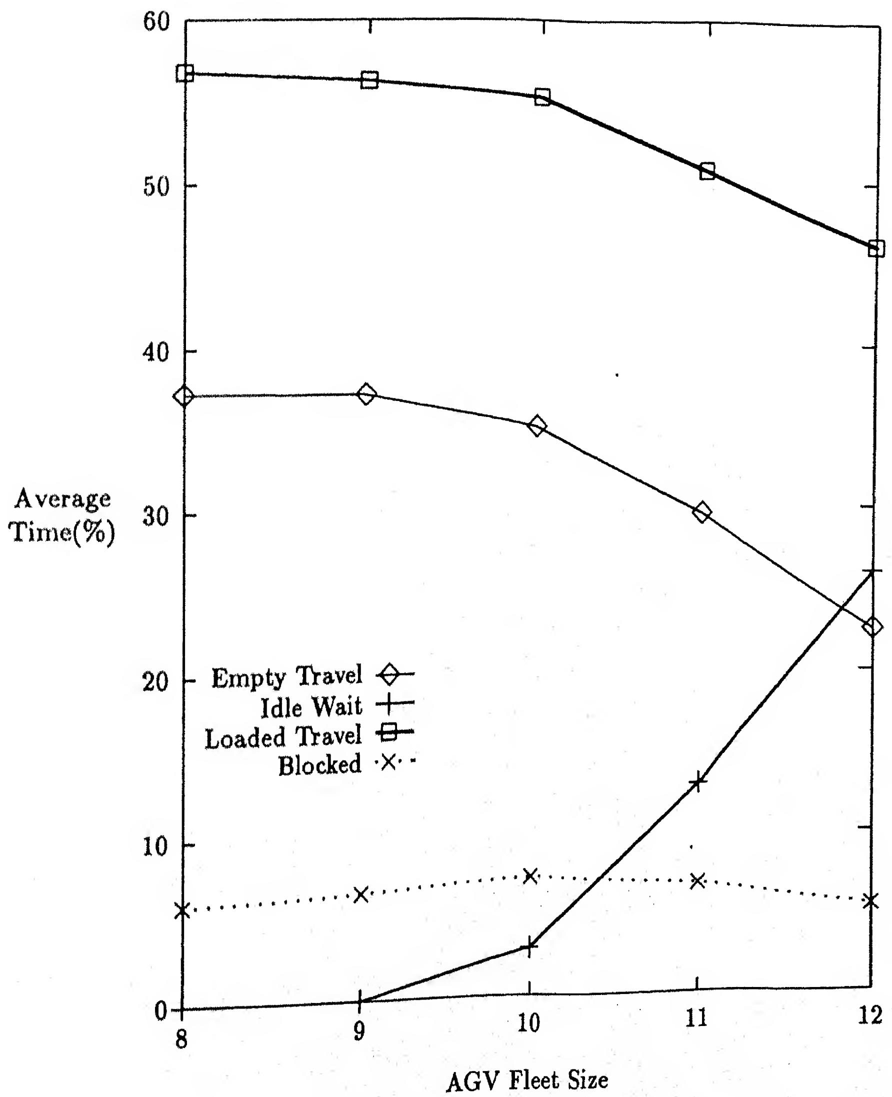

Figure 6.10: Distribution of vehicle activity time for Bi-III flow path design under the proposed routeing strategy

time also increases if a static routeing strategy is adopted. However, if the proposed routeing strategy is employed, then there is a considerable reduction in vehicle blocking time and the shop throughput rate is significantly improved.

Chapter 7

Conclusions

Automated guided vehicle systems have emerged as an important and critical component of modern FMSs. They are seen as interfacing and integrating links in CIMS environment because of the material handling flexibility they offer. Design and operational control of an AGVS is characterized by interactions among the design parameters and their cumulative impact upon the system operating dynamics. The present work is a study in design and operational characterization of AGVS. The design issues related to determination of optimal fleet size and flow path configuration, and the control measures related to vehicle dispatching and routeing strategies have been studied in details.

The issue of determination of optimal fleet size for an AGVS is of vital importance. It has bearing on economic justification for installing and operating the AGVS in an FMS environment. The number of vehicles required for performing a given level of material handling task depends on several factors, including the quantum of material to be moved in a given time period, the AGVS flow path layout together with the location of load transfer stations, vehicle dispatching and routeing strategies in operation, vehicle attributes, etc. The decision parameters are mutually inter-dependent and it is difficult to predict their individual impact upon the system performance. The decision process is further rendered tedious by the dynamic operating behaviour of the system which is typically exhibited in the form of empty vehicle travel. Due to the inherent randomness of FMS, empty

travel of vehicles cannot be determined accurately. Several analytical approaches have been advanced in the literature for explicitly and adequately capturing empty vehicle travel. A new model has been proposed in the present work. The objective of the model is to minimize the empty travels in a given manufacturing scenario, subject to the constraint that the vehicle fleet is to satisfy the material handling needs of the system. Thus, bounds have been placed on empty travels and a mixed integer linear programme has been formulated. The model has been applied on an FMS test facility and its results have been compared with those obtained from other analytical models. The follow-up simulation study has demonstrated that the proposed model, as well as some other models, estimate the required fleet size approximately same as that yielded by simulation model. This demonstration has been conducted for different operating conditions which include variation in job arrival rate and criticality of material handling resource. The results indicate that the proposed analytical model for estimating required fleet size can act as a good screening device prior to the simulation phase.

Designing the flow path layout for an AGVS is another vitally important issue in the overall AGVS design methodology. The flow path establishes the direction of traffic flow in the network and the routes followed by the vehicles. It affects material flow distances, vehicle requirement, space utilization, and overall system performance due to traffic congestion induced in the aisles and at the nodes. The operating behaviour of the system is directly manifested in the form of vehicle blocking phenomenon on account of the flow path design. Traditionally, unidirectional flow path design has been more frequently implemented in practice due to its simplicity in control structure and ease of traffic management. Bidirectional flows, though help in reducing material flow distances and improving system throughput, pose more challenging traffic control problems in the form of resolution of vehicle conflicts in the network. In the present work, a heuristic has been presented for the purpose of configuring a given unidirectional AGVS flow path layout into a hybrid uni/bidirectional one. The heuristic aims to reduce material flow distances in the network by selectively converting those unidirectional paths in the original network into bidirectional ones over which maximum material flow occurs to and

fro. The heuristic has been applied to the FMS test facility and two hybrid flow designs have been obtained. The effect of reduction in material flow distances on the system performance has been studied through simulation methodology. The study has demonstrated that the system throughput improves as the amount of bidirectionality is increased in the system. Fewer vehicles are required to achieve a specified throughput target. However, vehicle blocking time also increases as more paths are rendered bidirectional since the possibility of head-on conflicts in the traffic flow increases. Additionally, there is an increased requirement of vehicle sidings at the nodes in the network for the purpose of resolution of vehicle interference.

The ability of an AGV based MHS operating according to its promised potential is dependent upon the operational control measures in force. The selected control measures by which vehicles are assigned transportation tasks can affect material flow, buffer storage requirement, machine utilization, and vehicle effectiveness. Shop locking phenomenon is an important operating behaviour of the system which is directly influenced by the vehicle dispatching rules in operation and local buffer capacities in front of processing centres. Several vehicle dispatching rules have been discussed in the present work. These include push-type and pull-type vehicle initiated, and centre initiated rules. Simulation of the test facility has been carried out with an objective of studying the effectiveness of these rules on the system throughput rate and average queue lengths at local buffers. The study has demonstrated that the system throughput rate is sensitive to the vehicle dispatching strategies in operation. The distance based rules like nearest work centre (NW) lead to shop locking conditions. The buffer based rules like minimum remaining output queue space (mROQS) have potential in diffusing the shop locking conditions. The job attribute based rules like MFCFS help distribute the vehicles evenly in the network. The pull-type rules do not yield consistent throughput results. Centre initiated dispatching rules do not influence the throughput results. The simulation study also demonstrates how the vehicle dispatching problem and its associated resolution techniques can help in assessing the buffer space requirements at each centre.

The problem of vehicle route planning consists of the selection of a unique route

for any given vehicle mission, in such a way that the vehicle reaches its destination using the shortest defined path. In a static approach to route planning, the main criterion is to dispatch the vehicle by assigning it to the route associated with minimum distance to its destination. The possibility of traffic congestion and vehicle blocking under this routeing strategy is very high since same optimal routes are taken regardless of track congestion. Such an approach offers very little routeing flexibility. On the other hand, a dynamic approach to route planning offers a very high degree of flexibility since it takes into account forecasting traffic congestion status in order to avoid vehicle blocking. A semi-dynamic vehicle routeing strategy based on time windows has been presented. The approach involves placing reserved time windows at the nodes which indicate time intervals exclusively reserved for crossing by the respective vehicles. Free time windows between the reserved time windows are available for scheduling other vehicle crossings. Likewise, time windows are placed on bidirectional arcs indicating direction of traffic flow. Based on these time windows, Dijkstra's algorithm has been applied to find minimum blocking fastest routes for vehicles. The simulation study of the test facility has demonstrated that for the bidirectional AGVS networks, the shop throughput improves with the adoption of the proposed routeing strategy. This increase in throughput rate is due to less blocking time of the vehicles.

7.1 Scope for further work

The present work has emphasized the important issues in design and operational characterization of an AGVS. Besides these issues, there are many other aspects of this area of research which have scope for a detailed analysis. Some of these are described below.

There is a need for better and improved methods of estimating the fleet size, which take into consideration the AGV requirements in machining, assembly, warehousing, and other auxiliary requirements such as trips to and from the tool carousels and excess travels due to limited local/central buffers. Furthermore, a decision theoretic framework/approach can be constructed for selection of an appropriate

type of AGV from among the different types available in the market.

Not much work has been done in the use of AGVs in assembly lines. A detailed analysis can be done and models for desired throughput rates, cycle times or number of AGVs for such situations can be developed.

Analytical modelling of AGVS flow path design can benefit from computationally less complex methodologies like branch and bound algorithms. Such modelling should take into consideration the economic feasibility and justification for providing shortcuts, bypasses and sidings. Tandem configuration of the AGVS layout holds much promise on account of its modularity and simplicity in control structure. There is a need to develop a partitioning algorithm for dividing the AGVS network into non-intersecting single vehicle loops.

Intelligent vehicle dispatching rules can be devised for different manufacturing scenarios including flexible assembly lines, JIT, etc. These rules can take the shape of hierarchical heuristics emphasizing the shop operating conditions such as machine blocking or starvation.

There is a need to develop intelligent traffic control software for diverting blocked vehicles to less congested segments of the AGVS network. Such an intelligent transport controller will add to the benefits of free ranging AGVs.

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Appendix A

Source Code for a PMMLC Random Number Generator

```
# define MODULUS 2147483647
# define MULT1   24112
# define MULT2   26143

static long zrng [ ] =
{      0,
1973272912, 281629770, 20006270 }; /* 100 streams */

float rand ( int stream )
{
    long zi, lowprd, hi31;

    zi      = zrng [ stream ];
    lowprd  = ( zi & 65535 ) * MULT1;
    hi31    = ( zi >> 16 ) * MULT1 + ( lowprd >> 16 );
    zi      = (( lowprd & 65535 ) - MODULUS ) +
              (( hi31 & 32767 ) << 16 ) + ( hi31 >> 15 );
    if ( zi < 0 ) zi += MODULUS;
    lowprd  = ( zi & 65535 ) * MULT2;
    hi31    = ( zi >> 16 ) * MULT2 + ( lowprd >> 16 );
    zi      = (( lowprd & 65535 ) - MODULUS ) +
              (( hi31 & 32767 ) << 16 ) + ( hi31 >> 15 );
```

contd.

```
    if ( zi < 0 ) z i += MODULUS;
    zrng [ stream ]  = zi;
    return (( zi >> 7 | 1 ) + 1 ) / 16777216.0;
}

void randst ( long  zset, int stream )
{
    zrng [ stream ]  = zset;
}

long randgt ( int  stream )
{
    return zrng [ stream ];
}

float rand ( int stream );
void randst ( long  zset, int stream );
long randgt ( int  stream );
```

Appendix B

Mathematical Programme of the Proposed Model for Estimation of Empty Vehicle Travel Time

Minimize

$$\begin{aligned}
&1.5X_{12} + 3.5X_{13} + 3.5X_{14} + 5.5X_{15} + 4.5X_{16} + \\
&3.5X_{21} + 2.5X_{23} + 2.5X_{24} + 4.5X_{25} + 3.5X_{26} + \\
&1.5X_{31} + 2.5X_{32} + 4.5X_{34} + 6.5X_{35} + 5.5X_{36} + \\
&5.5X_{41} + 6.5X_{42} + 4.5X_{43} + 2.5X_{45} + 1.5X_{46} + \\
&3.5X_{51} + 4.5X_{52} + 2.5X_{53} + 2.5X_{54} + 3.5X_{56} + \\
&4.5X_{61} + 5.5X_{62} + 3.5X_{63} + 3.5X_{64} + 1.5X_{65}
\end{aligned}$$

subject to

$$\begin{aligned}
X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} &= 200 \\
X_{21} + X_{22} + X_{23} + X_{24} + X_{25} + X_{26} &= 120 \\
X_{31} + X_{32} + X_{33} + X_{34} + X_{35} + X_{36} &= 120 \\
X_{41} + X_{42} + X_{43} + X_{44} + X_{45} + X_{46} &= 100 \\
X_{51} + X_{52} + X_{53} + X_{54} + X_{55} + X_{56} &= 100 \\
X_{61} + X_{62} + X_{63} + X_{64} + X_{65} + X_{66} &= 140
\end{aligned}$$

contd.

$$X_{11} + X_{21} + X_{31} + X_{41} + X_{51} + X_{61} = 200$$
$$X_{12} + X_{22} + X_{32} + X_{42} + X_{52} + X_{62} = 120$$
$$X_{13} + X_{23} + X_{33} + X_{43} + X_{53} + X_{63} = 120$$
$$X_{14} + X_{24} + X_{34} + X_{44} + X_{54} + X_{64} = 100$$
$$X_{15} + X_{25} + X_{35} + X_{45} + X_{55} + X_{65} = 100$$
$$X_{16} + X_{26} + X_{36} + X_{46} + X_{56} + X_{66} = 140$$
$$X_{11} \leq 52$$
$$X_{22} \leq 19$$
$$X_{33} \leq 19$$
$$X_{44} \leq 13$$
$$X_{55} \leq 13$$
$$X_{66} \leq 26$$

Each X_{ij} is a non-negative integer.

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